Energy, Mines and Resources Canada | Énergie, Mines et Ressources Canada

CANMET

Canada Centre for Mineral and Energy Technology | Centre canadien de la technologie des minéraux et de l'énergie

MINERALOGY OF THE TULKS Zn-Pb-Cu MASSIVE SULPHIDE DEPOSIT, BUCHANS AREA, NEWFOUNDLAND

J.L. Jambor
Mineralogy Section
Mineral Sciences Laboratory

February 1984

Project: MRP-3.3.0.1.03
Mineralogical Studies of Marginal and Complex Ores

This document is an unedited internal report prepared primarily for discussion and internal reporting purposes. It does not represent a final expression of the opinion of the Canada Centre for Mineral and Energy Technology (CANMET)

Ce document est un rapport provisoire non révisé et rédigé principalement aux fins de discussion et de documentation interne. Il ne représente nullement l'expression définitive de l'opinion du Centre canadien de la technologie des minéraux et de l'énergie (CANMET)

5-4/140

JUL 20 1984

MICROMEDIA

MINERALS RESEARCH PROGRAM
MINERAL SCIENCES LABORATORIES
DIVISION REPORT MRP/MSL 84-22 (IR)

MINERALOGY OF THE TULKS Zn-Pb-Cu MASSIVE SULPHIDE DEPOSIT, BUCHANS AREA, NEWFOUNDLAND

by

J.L. Jambor *

ABSTRACT

The Tulks prospect is a pyritite-type massive sulphide deposit in felsic metavolcanics about 40 km southwest of Buchans. The deposit consists of four lenses, designated T-1 to T-4, which total 700,000 to 800,000 tonnes grading about 5.6% Zn, 2.0% Pb, 1.3% Cu, Ag 41 g/t, and Au 0.4 g/t. Pyrite is the principal sulphide in all of the Tulks lenses, and sphalerite, galena, chalcopyrite, and locally important tetrahedrite-tennantite account for all but trace amounts of the primary base metal values. Nearly all of the silver is attributable to argentian tetrahedrite-tennantite, and argentian native gold accounts for nearly all of the gold. Minor amounts of arsenopyrite occur in all lenses; minor magnetite, pyrrhotite, and marcasite are restricted to the T-1 and T-2 lenses. Several other oxides, sulphides, and tellurides occur in the deposit in trace amounts. The principal silicates are quartz, muscovite, and chlorite, and the main carbonate is dolomite. Albite, celsian, calcite, and barite are locally important. The chief minerals formed by oxidation and supergene alteration are digenite, covellite, and anglesite.

* Research Scientist, Mineral Sciences Laboratory, 555 Booth Street, Ottawa K1A 0G1

The textures and grain sizes of the Tulks sulphide minerals are suitable for liberation. Most of the base-metal sulphides are relatively coarse; finer fractions, even those in compact massive pyritite, are predominantly interstitial to pyrite or lie along pyrite grain boundaries. Textures are generally simple and grain boundaries are smooth; complex sulphide intergrowths are quantitatively rare. Unsatisfactory metal recoveries from tests of a deep underground sample from the T-3 lens are thought to be related mainly to the use of a grind too coarse for adequate liberation of the primary base-metal sulphides. On the other hand, the adverse effects of oxidation and supergene sulphides need additional testing because these alterations, although erratic, are more common at elevations above the level of the underground sample site.

MINÉRALOGIE DU GISEMENT DE SULFURES MASSIFS DE Zn-Pb-Cu DE TULKS RÉGION DE BUCHANS (TERRE-NEUVE)

par

J.L. Jambor*

RÉSUMÉ

Le gîte possible de Tulks, constitué d'un gisement de sulfures massifs, de type pyritite, se trouve dans des roches métavolcaniques felsiques, à environ 40 km au sud-ouest de Buchans. Le gisement se compose de quatre lentilles connues sous les noms de T1 à T4; ses réserves totales sont de 700 000 à 800 000 tonnes titrant environ 5,6 % de Zn, 2,0 % de Pb, 1,3 % de Cu, 41 g d'Ag/t et 0,4 g d'Au/t. La pyrite est le principal sulfure des lentilles de Tulks, alors que la sphalérite, la galène, la chalcopyrite, et par endroits en quantités importantes la tétraédrite et la tennantite renferment, à l'exception des quantités en traces, tous les métaux de base primaires. Presque tout l'argent vient de la tétraédrite et de la tennantite argentifères, et presque tout l'or d'or natif dans une gangue argentifère. On trouve de petites quantités d'arsénopyrite dans toutes les lentilles, et de petites quantités de magnétite, de pyrrhotine et de marcassite mais seulement dans les lentilles T1 et T2. Le gisement renferme des traces d'autres oxydes, sulfures et tellurures. Les principaux silicates sont le quartz, la muscovite et la chlorite et le principal carbonate est la dolomite. L'albite, la celsiane, la calcite et la barytine sont importantes par endroits. Les principaux minéraux formés par oxydation et par altération supergène sont la digénite, la covelline et l'anglésite.

---

* Scientifique, Laboratoires des sciences minérales, 555, rue Booth, Ottawa, K1A 0G1

Les textures et les granulométries des sulfures se prêtent bien au dégagement. La plupart des sulfures des métaux de base sont assez grossiers; les fractions plus fines, même celles qu'on trouve dans la pyrite massive, se trouvent surtout dans les interstices de pyrite ou le long des limites entre les grains de pyrite. Les textures sont généralement simples et les limites des grains lisses; les enchevêtrements complexes des sulfures sont rares. Les récupérations médiocres des métaux à partir des essais sur un échantillon profond de la lentille T3 seraient surtout liées à un broyage trop grossier pour le dégagement adéquat des sulfures de métaux de base primaires. Par contre, il est nécessaire de faire d'autres essais sur les effets contraires de l'oxydation et des sulfures supergènes, car ces changements, bien qu'irréguliers, sont plus communs dans des niveaux plus élevés que celui où l'on a prélevé l'échantillon.

INTRODUCTION

The Tulks prospect, held in cotenancy by Abitibi-Price Incorporated and ASARCO Incorporated, is a pyritite-type massive sulphide deposit about 40 km southwest of Buchans, central Newfoundland. The deposit, which is surficially marked by gossans, occurs in greenschist-facies felsic metavolcanics of presumed Ordovician age (Kean 1977). These felsic host rocks are reported by Barbour (1978) to be only about 1100 m thick in the Tulks area, but to have a strike continuity of more than 60 km. The rocks strike northeasterly, dip about 70^{o} northwest, and have their principal foliation parallel to the bedding.

Extensive diamond drilling by the Tulks cotenants was begun in 1963 and has since delineated four massive sulphide lenses, designated T-1 to T-4 (Fig. 1), which total 700,000 to 800,000 tonnes grading about 5.6% Zn, 2.0% Pb, 1.3% Cu, 41 g/t Ag, and 0.4 g/t Au. The T-1, T-2 and T-3 lenses are similar in size, tonnage and grade (Barbour 1978); each is exposed at surface and has a strike length of about 200 m, a depth of slightly more than 100 m, and an average thickness of 6 to 7 m. The T-4 lens is subsurface and extends from depths of approximately 100 m to 250 m. All of the massive sulphide lenses occur within larger tabular zones which average about 0.5% combined base metals, and these tabular zones are in turn enclosed within a much larger zone of disseminated pyrite in which the sulphide content is up to 20% but in which base-metal values are only at trace levels (Barbour 1978).

The Tulks T-3 lens has been penetrated by underground workings, from which a bulk sample taken for milling tests gave unsatisfactory metal recoveries. In a letter dated February 2, 1983, to W.G. Jeffery, Director-General, CANMET, it was stated by J.A. McGregor, Vice President, Abitibi-Price Mineral Resources,

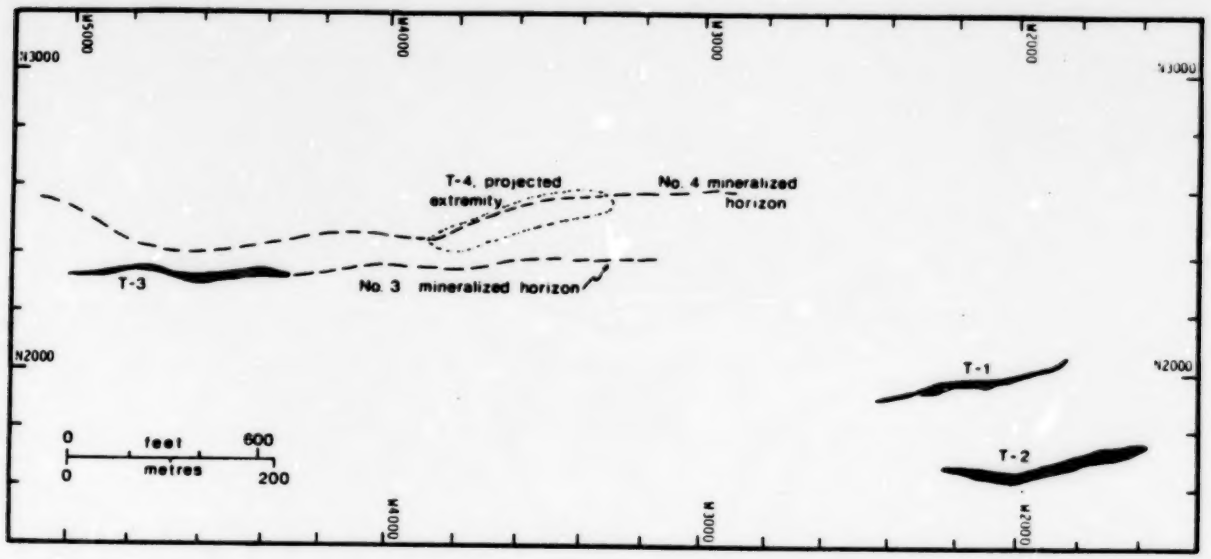

Fig. 1 - Distribution of the Tulks massive sulphide lenses, including the projected location of the subsurface T-4 lens. Values for the reference grid are in feet.

that the bulk sample for the milling tests was from low-grade, very pyritic mineralization on the edge of the main [T-3] lens, and that the presence of covellite created problems but "... it is not known if that mineral is ubiquitous". CANMET assistance was requested to pursue four main objectives, of which the first consisted of microscopic examination of diamond-drill cores from the T-1 and T-3 lenses, and the remainder dealt with possible additional bulk sampling and metallurgical tests.

To achieve the first objective, drill cores from the T-1, T-2, and T-3 lenses were sampled in detail during the 1983 field season. Although the main T-4 lens was not sampled, parts of the T-4 horizon adjacent to the T-3 lens were examined. Additionally, C.R. Powell, Mill Superintendent at Buchans, had taken the precaution of setting aside two sealed steel drums of coarsely crushed and sized feed derived from the mill tests of the Tulks bulk sample; several kg of

material from each drum were taken for mineralogical studies. The results reported herein are based on microscopic studies of 334 polished sections and 30 thin sections.

The geological maps and cross-sections in this report are based on maps and drillhole logs provided by Abitibi-Price Inc. The original data are in Imperial measures, which have been retained throughout this report, but an additional reference scale accompanies the Imperial one on all maps.

The term pyritite follows Schermerhorn's (1970) usage and denotes the highly sulphidic rock which makes up polymetallic stratiform sulphide masses containing a preponderance of pyrite. The name pyritite provides an instant distinction between the rock and the mineral, just as serpentine and serpentinite are conveniently distinguished.

GENERAL MINERALOGY

INTRODUCTION

Pyrite is the principal sulphide in all of the Tulks lenses, and sphalerite, galena, chalcopyrite and tetrahedrite-tennantite account for all but trace amounts of the primary base-metal values. Nearly all of the silver in the Tulks deposit is attributable to argentian tetrahedrite and tennantite; native gold is sufficiently common to account for nearly all of the gold detected by assay. A complete list of the minerals observed in this study is given in Table 1, and each is discussed below. General features are noted and pertinent electron microprobe analyses are included.

Hand specimens and drill cores of the Tulks massive sulphides are megascopically similar to pyritite from other deposits. Layering of the sulphides is commonly evident, particularly where both pyrite and sphalerite are the main

Table 1. Minerals in the Tulks deposit

Principal sulphides	Minor sulphides	Minor oxides	Others	
pyrite	arsenopyrite	magnetite	stannite	tetradymite
sphalerite	tennantite	ilmenite	kesterite	hessite
galena	pyrrhotite	hematite	gold	hedleyite(?)
chalcopyrite	tetrahedrite	cassiterite	silver	unidentified A (Bi_3Te_2)
			bismuth	unidentified B (Bi_2Te)

Principal silicates	Sulphates, carbonates, etc.	Oxidation and supergene assemblages	
quartz	dolomite	digenite	anglesite
muscovite	calcite	covellite	kaolinite
chlorite	barite	marcasite	cerussite
albite	siderite		goethite
celsian	ankerite		
	apatite		

constituents of a rock. The two minerals usually show some degree of segregation, and the assemblage is generally the only one commonly to display thin laminations of sulphides. Layering of sulphides is also commonly evident where the amount of silicates accompanying the sulphides is large. Thus layering arises mainly through variations in the proportions of pyrite and base-metal sulphides, but also arises through changes in pyrite grain sizes. The Tulks pyritite is generally fairly coarse, with pyrite grain sizes commonly exceeding 0.5 mm. This coarseness is readily apparent in hand specimens.

PYRITE

The pyrite is euhedral to anhedral and coarse to fine-grained, but even the finest grained samples lack colloform or framboidal textures and growth zoning.

The general trend - though exceptions are common - is to have anhderal forms where most of the pyrite grain boundaries are in mutual contact, and to have euhedral to subhedral forms where the pyrite grains are separated. The latter, well-crystallized pyrite is the more abundant form at Tulks. In sphalerite-rich layers the well-crystallized pyrite is usually coarse-grained and moderately to extensively corroded. In samples consisting predominantly of fine-grained, coalesced grains of well-crystallized pyrite, a common feature is to have the base-metal sulphides disposed to interstices among the pyrite grains. Pyrite triple-point junctions are rare.

SPHALERITE

Tulks sphalerite is megascopically brown rather than black, in keeping with the low iron content of the mineral (Table 2). Most of the sphalerite is associated with abundant pyrite, but in a few places sphalerite layers poor in pyrite are interbedded with the metavolcanics and are sufficiently abundant to form semi-massive sulphides. Under the microscope, the most notable feature of the bulk of the Tulks sphalerite is its homogeneity: coarse grains in smooth contact with other minerals, and finer grains among the interstices of pyrite account for by far the greatest part of the zinc values, both in high-grade and low-grade samples.

Complex intergrowths of sphalerite and galena, or sphalerite-galena-chalcopyrite, have been observed in several samples; nevertheless, the amounts involved in these intergrowths are a minutely small fraction of the total volume of base-metal sulphides and thus are not considered to be a serious impediment to ore-mineral liberation. The most striking of the intergrowths, though rarely found, are in extremely high-grade Pb-Zn samples wherein some of the sulphides approach a coarse emulsion texture. Much more common is sphalerite which contains abundant minute blebs of chalcopyrite, typical of the association

Table 2. Electron microprobe analyses of Tulks sphalerite

Lens	T-1	T-1	T-3 W4940	T-3 W4940	T-3 W4800	T-3 W4800	T-3 W4705
Sample number*	T-2-34	T-2-44	T-62-55	T-62-57	T-60-59	T-96-132	T-99-119
Wt. % Zn	65.1	57.7	64.5	63.9	62.4	64.5	65.2
Fe	2.0	8.6	2.7	3.0	4.2	1.9	1.8
Cd	0.5	0.5	0.2	0.2	0.2	0.2	0.2
Mn	0.0	0.1	0.1	0.1	0.1	0.1	0.0
S	32.9	33.1	33.2	33.0	33.1	32.7	32.9
	100.5	100.0	100.7	100.2	100.0	99.4	100.1

* Drillhole number and footage

Operating conditions: 20kV accelerating voltage, 0.025-0.030 μA specimen current; 10-second counting times (20 sec. for Mn, Cd); standards used: synthetic sphalerite No. 20 and No. 22, synthetic CdS and MnS. Limit of detection for Mn is 0.03%.

commonly referred to as exsolution texture. The blebs are almost invariably randomly distributed rather than crystallographically aligned. Although sphalerite of this type was observed in numerous polished sections, in nearly all cases the grains are associated with additional sphalerite that is homogeneous and much more plentiful. Thus the exsolution-type grains, despite their widespread spatial distribution, constitute only a fraction of a per cent of total sphalerite at Tulks.

Electron microprobe analyses of several grains of Tulks sphalerite are given in Table 2. Cadmium contents range from 0.2 to 0.5 wt % whereas the manganese reaches a maximum of 0.1% and is below the limit of detection in two samples. Iron contents are generally low where sphalerite in contact with various sulphides and silicates, but is high for the single analyzed sample (T-2-44) in which the sphalerite is in contact with pyrrhotite.

GALENA

Galena at Tulks is usually associated with sphalerite and is almost invariably subordinate to it in both quantity and grain size. Grain boundaries between the two minerals are generally simple and regular. Most of the galena occurs as large to small homogeneous patches in the sphalerite, as patches concentrated at the rims of sphalerite, or as grains interposed between pyrite and sphalerite. Penetrative replacement of sphalerite by galena is present occasionally, but well-defined, cross-cutting linear veinlets of galena are extremely rare. An unusual feature observed in a few samples is the occurrence of galena as hairline rims on sphalerite, usually separating the sphalerite from non-sulphide gangue. The rims resemble those formed by supergene digenite and covellite, and thus energy-dispersive X-ray analyses were used to confirm that the rims are galena rather than chalcocite.

In massive, compact pyritite, galena (and sphalerite) occupy the interstices among pyrite grains or crystals (Fig. 2). The predominant trend in these occurrences is to have the interstitial sulphides segregated, that is, with some of the interstices occupied solely or predominantly by galena, and others by sphalerite (or other minerals). Where the two do share an interstitial site, short simple contact rather than irregular intergrowth is the rule.

The above associations account for the bulk of the galena, but appreciable amounts of the mineral also occur as narrow elongate grains resembling veinlets along pyrite grain boundaries, and as inclusions in pyrite crystals. The inclusions are generally round to oval, occasionally irregular, and most are monomineralic. They are widespread in all lenses, but are much less abundant than similar inclusions of sphalerite. Sizes of the inclusions are highly variable, but grains greater than 20 micrometers in diameter account

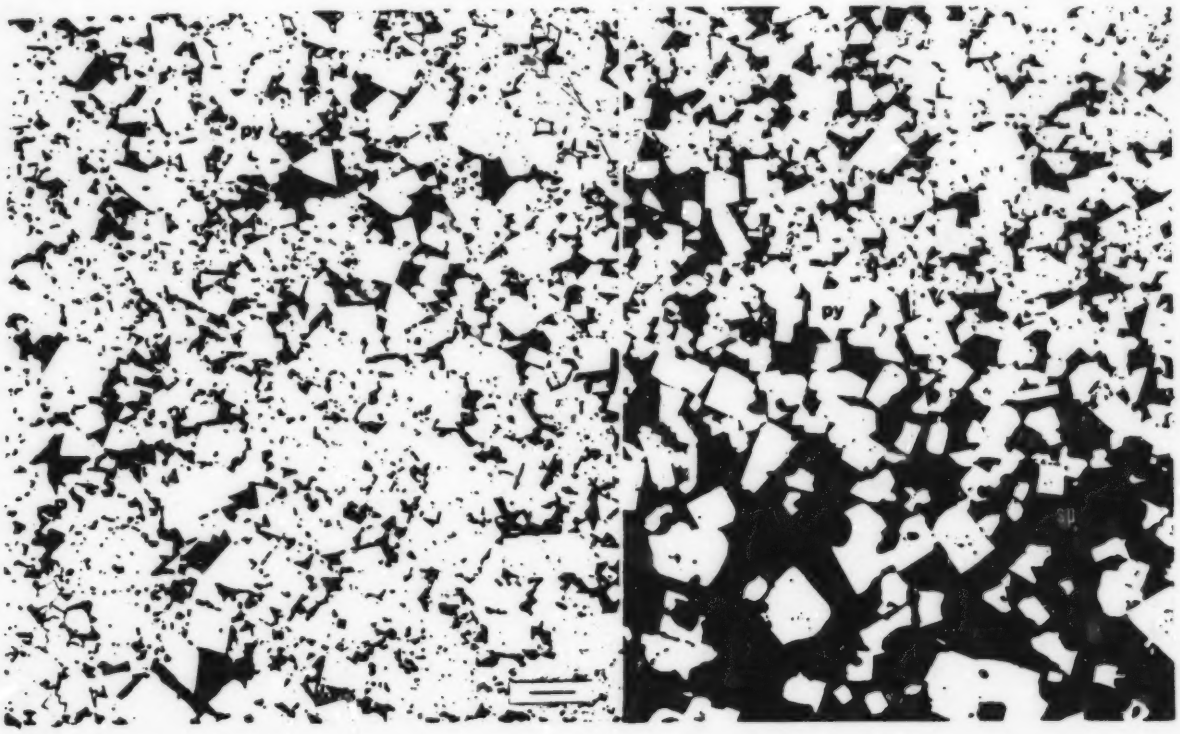

Fig. 2 - Interstitial texture consisting mainly of light-coloured pyrite with dark grey sphalerite among the interstices of the pyrite grains. Right-side photo shows interstitial texture gradational to a sphalerite-rich layer containing abundant pyrite crystals, commonly corroded. (Left photo from drillhole T-71 at 93 feet, right photo from T-1 at 44 feet; reflected light, air, with both photos at same magnification; bar scale represents 0.1 mm).

for the main volume of this type of occurrence. In a few extremely low-grade pyritite samples, inclusions are the main source of the low base-metal values.

Because of time constraints coupled with inadequate microprobe facilities, analyses of Tulks galena have not been done. Although argentian tetrahedrite and tennantite are apparently sufficiently abundant and widespread to account for nearly all of the Tulks silver, the possibility of solid-solution silver in galena cannot be discounted.

CHALCOPYRITE

Nearly all of the primary copper values in the T-1, T-2, and T-3 lenses are attributable to chalcopyrite. In contrast, tennantite is the principal copper carrier in the eastern part of the T-4 horizon (Fig. 1). Tennantite also is locally abundant in parts of the T-3 lens, such at section W4800 (Fig. 19), but overall merely supplements the copper values derived from chalcopyrite.

Most of the chalcopyrite occurs along pyrite grain boundaries and in the interstices among pyrite crystals, as larger patches which have coalesced to form the matrix hosting pyrite crystals, and as large homogeneous patches in sphalerite and in silicate gangue. The interstitial-type occurrence is especially characteristic of tightly compact pyritite low in silicates and galena-sphalerite.

Chalcopyrite in contact with galena or sphalerite usually has smooth grain boundaries, but incidental sutured contacts occur where patches of chalcopyrite have irregularly replaced sphalerite. A few large chalcopyrite grains contain abundant silicate inclusions, but sulphide inclusions other than pyrite are uncommon. Chalcopyrite bleb inclusions in pyrite occur much less frequently than those of sphalerite.

MINOR SULPHIDES

The principal sulphides listed in Table 1 make up the bulk of the Tulks sulphide assemblage and also are the most important in terms of pervasive distribution and economics. The four minor sulphides listed in Table 1, although abundant locally, nevertheless constitute only a small percentage of the Tulks pyritite and have a restricted rather than a pervasive spatial distribution.

Arsenopyrite is widespread in that it occurs in all of the Tulks lenses. Maximum volume of arsenopyrite in an individual polished section is about 10 %,

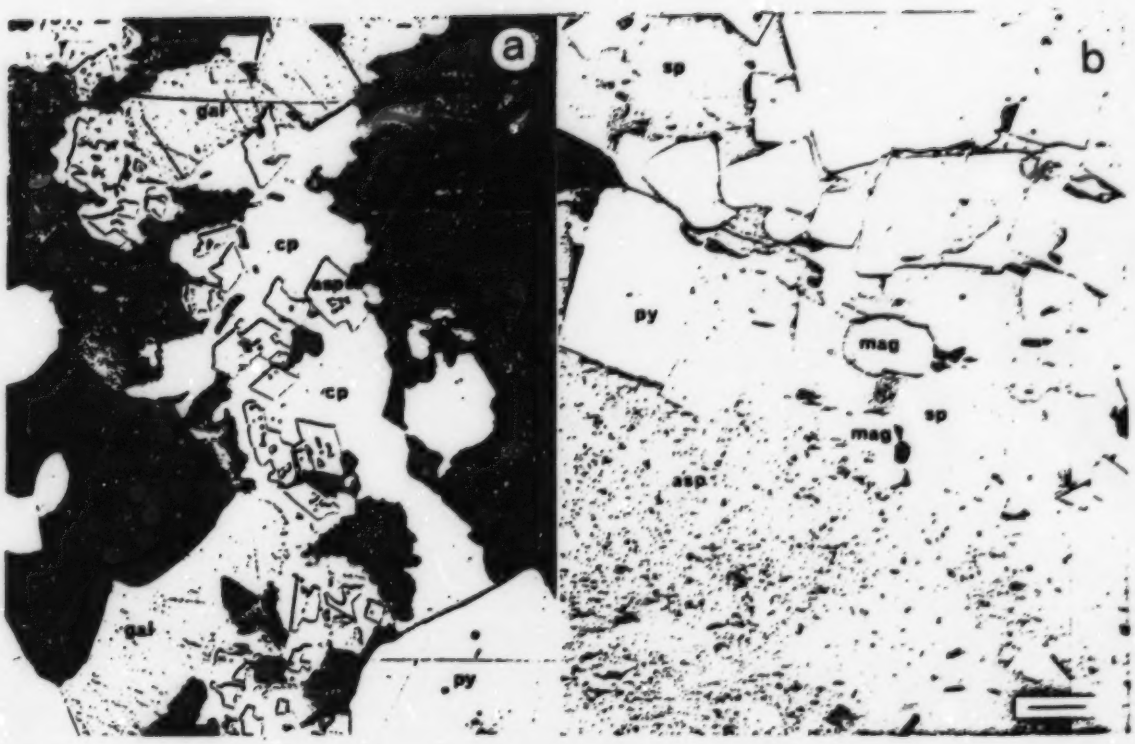

Fig. 3 - (a)Typical occurrence of arsenopyrite: a group of arsenopyrite grains (asp) enclosed in chalcopyrite (cp), with associated tennantite (tenn), galena (gal) and sphalerite (sp). Sample T-99-114, reflected light, oil immersion.
(b)Atypical form of arsenopyrite: fine-grained cloud in sphalerite with anhedral magnetite (mag). Sample T-1-41, reflected light, air. Both photos at same magnification; bar scale represents 0.05 mm.

but in many sections the mineral is absent.

Almost all of the arsenopyrite occurs in two forms, the more abundant of which consists of dispersed euhedral to subhedral crystals or crystal clusters. The crystals may be fine-grained and disseminated amidst pyrite, but more commonly are coarse, with individuals up to 0.5 mm in length. The less abundant

of the two principal forms consists of clusters of arsenopyrite grains, many of them euhedral, which are typically largely to completely enclosed within an island of chalcopyrite (Figs. 3a, 7).

Minor amounts of arsenopyrite occur in other forms, such as the extremely fine-grained clouds aggregated in sphalerite as shown in Figure 3b. The abundance and distribution of arsenopyrite and other minor minerals in each of the Tulks lenses are discussed later. Quantitative estimations of these minerals were obtained by comparing the microscopic observations with American Geological Institute reference diagrams representing various percentages of grains.

Tennantite has a widespread distribution and is occasionally sufficiently abundant that masses are megascopically identifiable in drill cores. Tetrahedrite, the antimony analogue of tennantite, also occurs at Tulks but is much less abundant as indicated by correlations between microscopic observations and microprobe analyses. The two minerals form a solid-solution series, the members of which are not readily separable by optical microscopy, and thus they are referred to here without distinction under the single name tetrahedrite-tennantite.

All of the Tulks tetrahedrite-tennantite occurs as anhedral grains which vary in size from micrometers to millimeters: the main volume of tetrahedrite-tennantite is not concentrated in any particular narrow size range. In several of the "sparse" occurrences (e.g. Fig. 15) the grains average less than 25 micrometers in diameter and are locked as round inclusions in pyrite. This type of association accounts for less than 5 volume per cent of the tetrahedrite-tennantite, and most of the remainder is interstitial to pyrite or along its grain boundaries, or occurs as smooth-bounded grains of random shape in sphalerite. Contacts with galena and chalcopyrite generally are smooth too, though both minerals on occasion show an irregular, penetrative replacement limited to tetrahedrite-tennantite grain margins.

Table 3. Electron microprobe compositions of Tulks tetrahedrite-tennantite

Lens	T-1		T-1		T-3 W4940			
Sample number*	T-1-42		T-2-34		T-62-55			
	area A	area B	av.	range	area A av.	area A range	area B av.	area B range
Wt. % Cu	41.0	41.3	41.0	-	31.6	30.4-34.4	35.6	34.2-37.1
Ag	1.2	1.0	1.2	0.9-1.7	10.3	7.4-12.3	4.9	4.2-5.4
Fe	5.1	4.6	4.4	-	4.0	-	5.6	-
Zn	3.2	3.2	3.5	-	3.2	-	3.0	-
Sb	7.3	7.1	14.4	9.4-18.4	26.3	22.6-28.3	17.0	14.5-21.0
As	15.3	15.5	10.6	7.8-14.1	1.9	0.6-2.4	8.1	6.0-10.2
S	28.1	27.9	27.1	-	24.5	-	25.8	-
	101.7	100.6	102.2		101.8		100.0	

Lens	T-4 W4705	T-4 W4705	T-3 W4705	T-3 W4705	T-3 W4705
Sample number	T-99-38	T-99-42	T-99-113	T-99-119	T-99-123
Wt. % Cu	41.8	41.7	43.2	42.4	42.3
Ag	0.2	0.2	0.4	0.5	0.7
Fe	4.3	4.5	5.8	5.8	5.8
Zn	3.7	3.6	2.5	2.6	2.5
Sb	8.9	7.9	1.3	2.6	2.3
As	14.2	14.7	19.3	18.1	18.8
S	27.7	28.0	29.0	28.5	29.1
	100.8	100.6	101.5	100.5	101.5

* Drillhole number and footage

Operating conditions and standards as in Table 2. Additional standards: natural enargite (As$K\alpha$), synthetic CuFeSbS (Cu$K\alpha$), and natural tetrahedrite (S$K\alpha$, Fe$K\alpha$, Sb$L\alpha$, Ag$L\alpha$).

Microprobe analyses of several grains of tetrahedrite-tennantite are given in Table 3. Compositions vary from almost end-member tetrahedrite to almost end-member tennantite, and individual grains vary from those that are homogeneous to those with a considerable range in composition (Table 3). Silver is present in all of the analyzed grains; the amounts are generally low in tennantite and moderate in tetrahedrite. The highest silver value, 12.3 wt.%, coincides with the most antimony-rich of the tetrahedrite analyses.

Blebs of pyrrhotite occur sparingly as inclusions in pyrite in all of the Tulks lenses. Most of the inclusions are round and 15 to 20 micrometers in diameter; many of the individuals consist of both pyrrhotite and chalcopyrite. Coarse grains of pyrrhotite, similar in size to those of the base-metal sulphides, occur only in the T-1 lens. The distribution of the mineral in the W2000 cross-section is shown in Figure 16.

Crystallization of pyrrhotite apparently occurred mid-way in the sulphide paragenetic sequence. Some of the pyrrhotite grains are interstitial to pyrite and have partly replaced arsenopyrite. Replacement of sphalerite is less distinct and consists mainly of pyrrhotite penetration, with some of the protuberances suggesting veining of the sphalerite. On the other hand, pyrrhotite appears to have been replaced by chalcopyrite, and veining of pyrrhotite by galena is obvious.

Much of the pyrrhotite has been altered as shown in Figure 4. The alteration consists mainly of extremely fine-grained marcasite, in some cases accompanied by equally fine-grained secondary pyrite, which rims and veins the pyrrhotite. Substantial pitting along the borders of the veinlets (Fig. 4) is indicative of the volume reduction which attends the transformation of pyrrhotite to marcasite (Fleet, 1978).

Fig. 4 - Alteration of pyrrhotite to fine-grained marcasite veinlets accompanied by severe pitting along the veinlet margins. Sample T-2-44, reflected light, oil immersion. Bar scale represents 0.05 mm.

Fig. 5 - Pyrite with interstitial chalcopyrite (cp) and large grains of anhedral magnetite (mag) riddled with pyrite inclusions. Sample T-2-38, reflected light, air. Bar scale represents 0.10 mm.

Fig. 6 - Coexisting rutile (ru) and ilmenite (ilm) in silicate gangue (black). Sample T-52-24, reflected light, oil immersion. Bar scale represents 0.05 mm.

Fig. 7 - Large grains of gold in chalcopyrite and arsenopyrite of the type shown in Figure 3a. Sample T-99-114 (Table 4), reflected light, oil. Scale represents 0.025 mm.

MINOR OXIDES

Magnetite was found in the T-1 and T-2 lenses but was not observed in the T-3 or the examined part of the T-4 lenses. The distribution of the mineral in the T-1 lens is shown in Figure 15. In the T-2 lens, magnetite occurs only in drillhole T-61 (Fig. 14). The massive sulphide zone in T-61 extends from 165.5 to 185.5 feet, whereas magnetite occurrences are restricted to the interval from 174 to 183 feet, inclusive, but are continuous throughout this interval. Abundance of the magnetite ranges from ½ to 2 volume per cent.

Most of the Tulks magnetite occurs as homogeneous subhedral to anhedral grains which average about 0.02 mm along an edge. Large anhedral grains, up to 0.3x0.4 mm, also are common and some are riddled with small inclusions of pyrite (Fig. 5).

Hematite occurs only in trace amounts as replacement rims and laths associated with magnetite in drillhole T-61. The replacement may be related to post-crystallization oxidation and supergene enrichment processes, but the occurrence of some of the hematite as laths with razor-sharp margins in magnetite, as well as the association of hematite laths with siderite that replaced magnetite, suggests that the hematite may be a primary mineral.

Ilmenite was found in numerous polished sections from the various Tulks lenses. The mineral has been noted to occur both amidst the massive sulphides and in the intercalated micaceous host rocks, always in small amounts and usually with rutile. Subhedral to anhedral grains and granular clusters of rutile are typically concentrated along layers that serve to enhance the original bedding, and the mineral is thought to be part of the original rock-forming assemblage. Ilmenite is much less abundant than rutile, but their occasional coexistence and identical morphology (Fig. 6) suggests that ilmenite may have

been derived by alteration of rutile.

Cassiterite is difficult to identify in polished sections and thus little is known about its occurrence in the Tulks deposit. The mineral fluoresces under the beam of the electron microprobe, and this property led to its detection in a stannite-bearing sample from drillhole T-71 (T-3 lens, section W4800).

OTHERS

This category includes silver and gold, stannite and kesterite, and bismuth tellurides (Table 1). Although all are volumetrically insignificant, the gold occurrences adequately account for the ore-reserve average of 0.4 g/t Au.

Gold and silver form a solid-solution series in which the boundary for Au:Ag=1:1 is at 64.6 wt. per cent Au. Microprobe analyses of Tulks gold (Table 4) show that most grains contain substantial amounts of silver, and that in one grain the formula ratio of gold is subordinate to that of silver. Nevertheless, for convenience all occurrences will be referred to as gold.

Gold has been observed to occur only in the T-1, T-2, and T-3 lenses; its apparent absence from the T-4 horizon probably merely reflects the relatively few samples examined from this zone. The largest area of gold found in this study is shown in Figure 7; the mineral typically occurs as blebs which average 5 to 15 by 20 micrometers in size, and occasionally occurs as worm-like grains. Almost all of the gold grains are inclusions in chalcopyrite, and in about half of the occurrences arsenopyrite of the type shown in Figure 7 also is present.

Stannite and kesterite are closely related minerals having the composition $Cu_2(Fe,Zn)SnS_4$ and $Cu_2(Zn,Fe)SnS_4$, respectively. Partial substitution of Fe and Zn occurs, but at low temperatures the two minerals are separated by a miscibility gap (Kissin and Owens, 1979). At Tulks, stannite and kesterite are intergrown in worm-like and irregular grains up to 40x60 micrometers. Most of the grains

Table 4. Electron microprobe analyses of Tulks silver and gold

Lens	T-1	T-3 W4940	T-3 W4940	T-3 W4705	T-3 W4705	T-3 W4400
Sample number*	T-1-39.5	T-62-55	T-62-57	T-99-114	T-99-119	T-114-158
Wt. % Au	53.0	69.1	66.7	83.0	82.5	76.9
Ag	45.5	30.6	34.0	18.5	19.2	23.3
	98.5	99.7	100.7	101.5	101.7	100.2
Formula ratio Au	38.9	55.3	51.8	71.2	70.2	64.3
Ag	61.1	44.7	48.2	28.8	29.8	35.7

*Drillhole number and footage

Analytical conditions as in Table 2; synthetic $Au_{60}Ag_{40}$ used as a standard.

are disseminated in sphalerite (Fig. 8), but stannite rims on sphalerite also have been observed. The tin sulphides occur in the T-1 and T-3 lenses, particularly in drillhole T-96 (W4800, Fig. 17).

Tellurides occur in trace amounts in the T-3 lens, especially in an unusually coarse pyrite-chalcopyrite assemblage which makes up the main sulphide intersection in drillhole T-178 (W4400, Fig. 21). The most common telluride is tetradymite (Bi_2Te_2S), whose identification has been confirmed by microprobe analyses (Table 5) and X-ray powder diffraction patterns. Most of the tetradymite occurs at the centres of irregularly zoned telluride intergrowths (Fig. 9), but a few homogeneous, unzoned grains also have been found. The perimeter of zoned

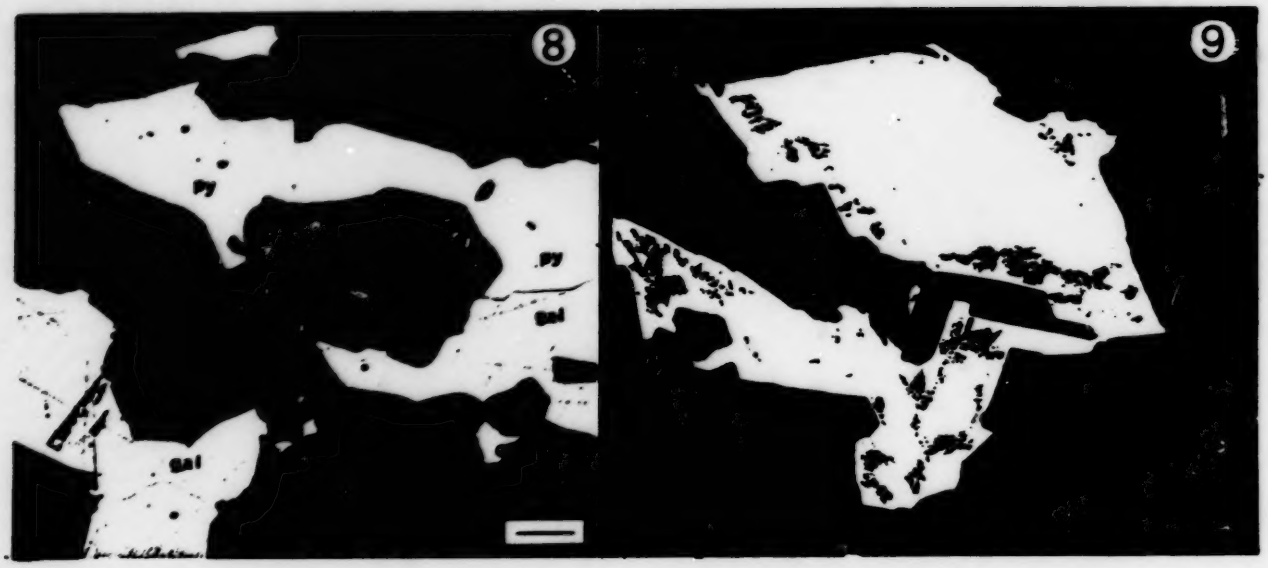

Fig. 8 - Blebs of stannite-kesterite in dark grey sphalerite (sp) with adjacent galena (gal) and remnant pyrite (py). Sample T-96-132, reflected light, air. Bar scale represents 0.05 mm.

Fig. 9 - Electron back-scatter image of zoned tellurides in sample T-178-149. A core of tetradymite is partly surrounded by a dark intergrowth containing hessite, and rimmed by a white perimeter of unidentified A.

grains, such as that shown in Figure 9, consists of an unidentified telluride whose composition corresponds to Bi_3Te_2 (unidentified A in Table 5). The zone between the tetradymite core and the Bi_3Te_2 rim is commonly a complex intergrowth containing patches of hessite (Table 5). The complex intergrowth averages about Pb 24, Ag 44, Te 29, and S 4 wt %. One grain consists of a core of the intergrowth surrounded by an aggregate of laths whose composition corresponds to Bi_2Te (unidentified B, Table 5). Also present in the T-178 assemblage are minute grains of a mineral which occurs at the edges of pyrite crystals, and which has the composition of hedleyite (Table 5).

Table 5. Electron microprobe compositions of Tulks tellurides

		tetradymite		hedleyite(?)		hessite	unident. A		unident. B	
		(a)	(b)	(a)	(b)		(a)	(b)	(a)	(b)
Wt. %	Bi	60.5	60.7	80.2	78.8		69.9	69.6	76.8	74.1
	Ag	-	-	-	-	61.9	-	-	-	-
	Te	35.5	35.8	20.5	21.2	39.0	28.8	30.2	23.5	22.2
	S	4.4	4.5	-	-	-	-	-	-	-
		100.4	101.0	100.7	100.0	100.9	98.7	99.2	100.3	96.3
Formula ratio	Bi	2.06	2.04	7.05	6.94		2.98	2.92	2.00	2.02
	Ag					1.96				
	Te	1.97	1.98	2.95	3.06	1.04	2.02	2.08	1.00	0.98
	S	0.97	0.98							
Theoretical		Bi_2Te_2S		Bi_7Te_3		Ag_2Te	Bi_3Te_2		Bi_2Te	

All analyses are of grains in sample T-178-149. Analytical conditions as in Table 2. Standards: synthetic PbTe (Pb$L\alpha$), synthetic Bi_2Te_3 (Bi$L\alpha$), pure Ag (Ag$L\alpha$), synthetic PbS (S$K\alpha$).

tetradymite: (a) core of zoned grain similar to that in Figure 9
(b) homogeneous grain occurring as an inclusion in pyrite

hedleyite(?): minute grains at edge of pyrite

hessite: intermediate phase of zoned grain similar to that in Figure 9

unidentified A: white perimeter of zoned grain similar to that in Figure 9

unidentified B: laths which protrude into, and partly surround a core of a complexly intergrown mixture consisting partly of hessite

Traces of tellurides also occur in drillhole T-170 (section W4940). One veinlet which cuts across the tip of a large galena grain consists of hessite, native bismuth, and a bismuth telluride.

PRINCIPAL SILICATES

The mineralogy of the felsic metavolcanic host rocks has been described by Barbour (1978); the principal silicates referred to here (Table 1) are the components which occur in samples of massive sulphides, and thus are quantitatively minor relative to the associated sulphides.

Quartz is ubiquitous and is the only silicate in many samples, particularly those with an extremely high sulphide content. The most conspicuous megascopic form of quartz is its occurrence as irregular ramifying veinlets, 1 to 2 mm wide, which cut the sulphides in numerous samples. Less conspicuous, but by far the most important in quantity, are quartz grains and aggregates which occur simply as dispersed patches among the sulphides. The grains are typically anhedral, roughly equant rather than elongate, and nearly all are greater than 60 micrometers in diameter.

Muscovite is present in at least trace amounts in most samples and is the principal silicate in some. The mineral is characteristically well crystallized and lath-like. Single laths up to one millimetre long have been observed, and finer grained aggregates in massive sulphides usually consist of a coalescence of laths rather than shreddy or sheaf-like bundles.

X-ray powder diffraction patterns of the muscovite associated with massive sulphides consistently indicate a $2M_1$ structure, but compositional abnormality

is suggested by the presence of diffraction-line shifts. Although microprobe analyses of the muscovite have not been obtained, energy dispersion analysis of laths in the barium-rich assemblage from drillhole T-1 indicated that the mica contains percentage amounts of BaO.

Chlorite is widely distributed but seems to occur more erratically than muscovite, with which it is nevertheless commonly associated. Some of the chlorite occurs as laths, but this form is less persistent and generally finer grained than for muscovite. Partial replacement of muscovite by chlorite along grain edges and along cleavage has been observed in some samples. X-ray powder diffraction patterns of a few chlorite samples consistently indicated that the structure is that of the IIb polytype.

Albite is widely distributed even though it forms only a low fraction of a per cent of the silicate gangue. In most occurrences the mineral is present as a grain, or a few grains, which are anhedral, polysynthetically twinned, and isolated amongst the sulphides. In a few places the grains are up to 0.5 mm wide. Albite aggregates up to a centimetre in diameter also have been observed.

Celsian, $BaAl_2Si_2O_8$, is common throughout the massive sulphide zone intersected in drillhole T-32 (Fig. 14). The mineral occurs among the sulphides as elongate grains up to 1.0x0.6 mm, and also as slightly smaller grains which are irregular but roughly equant in outline. Some grains are homogeneous; others contain numerous pyrite inclusions and patches of dolomite. Minor substitution of K for Ba has been detected by energy dispersion analysis.

The celsian-bearing zone possibly is confined to the T-1 lens, but apparently is extensive within the lens. Thin sections of samples from drillholes

T-1 and T-2 also contain celsian, though the predominant gangue is quartz, chlorite and barite accompanied by lesser amounts of muscovite and dolomite. Additional study of the Tulks silicate assemblage would be of particular mineralogical interest because traces of unidentified minerals, including a barium-titanium silicate, have been noted in the celsian zone.

SULPHATES, CARBONATES, ETC.

The principal minerals in this category are dolomite and, to a lesser extent, calcite. Barite is the main mineral of this group in some samples, but is not widespread in occurrence. Siderite, ankerite, and apatite are rare.

Dolomite and calcite have been found in all of the Tulks lenses as fine-grained aggregates and coarser single grains dispersed among the sulphides. The occurrences are similar to those of quartz, and in most samples the carbonates coexist with silicates, particularly where the spaces between the sulphides are sufficient to form an interconnecting network. Rare, irregular patches of white dolomite up to 1.5x1.5 cm have been observed, and numerous polished sections contain dolomite areas which are roughly 1 to 2 mm in diameter. Dolomite and calcite usually occur together, though either may be almost exclusive in an individual polished section.

X-ray powder diffraction patterns of dolomite from 16 samples gave normal cell dimensions except for 3 which have enlarged cells indicating probable Fe or Mn substitution for Mg. Microprobe analysis of one of the areas (T-96, Table 6) shows that the cell enlargement is mainly related to Mn substitution, whereas in another area (T-61, Table 6) the enlargement reflects the presence of ankerite.

The analyzed ankerite from drillhole T-61 coexists with siderite and

Table 6. Electron microprobe analyses of Tulks ankerite and Mn-rich dolomite

	ankerite (T-61-176)			Mn-rich dolomite (T-96-140)		
	wt. %	proportions		wt. %	proportions	
CaO	28.0	1.000		28.1	1.000	
MgO	18.8	0.413		14.8	0.731	
FeO	8.3	0.523	0.986	3.2	0.090	1.069
MnO	1.8	0.050		8.8	0.248	
	56.9			54.9		

Analytical conditions as in Table 2, but with rhodochrosite, dolomite and synthetic Fe_2O_3 used as standards.

hematite laths which have replaced part of a large magnetite grain. Siderite was also identified as a component of a veinlet, less than ½ mm wide but almost 2 cm long, which is normal to the layering of massive sulphides in drillhole T-51.

Barite has been identified only in samples from the T-1 and T-2 lenses; the lack of detection of the mineral in the T-3 lens may merely reflect that nearly all the T-3 rocks examined in thin sections are from the underground bulk-sample site, but the apparent absence of the mineral nevertheless emphasizes its subordinate position in the gangue assemblage.

In the T-1 and T-2 lenses, barite is associated with quartz and carbonates as disseminated grains among the sulphides. The most abundant occurrence is in drillhole T-32 (Fig. 14), where the proportion of barite varies in harmony with the layering of the sulphides. No massive barite was found in this study.

A member of the apatite group, possibly fluorapatite, was identified by X-ray diffraction patterns of a massive sulphide sample from the T-4 lens. The apatite is a minor constituent in a gangue assemblage which consists mainly of dolomite and quartz.

OXIDATION AND SUPERGENE ASSEMBLAGES

The supergene sulphides are digenite, covellite and marcasite. The first two are widespread, whereas marcasite has been found only in the T-1 and T-2 lenses.

The distribution and abundance of marcasite in the T-1 lens are shown in Figure 16. Much of the marcasite is associated with vestiges of precursor pyrrhotite (Fig. 4). Some of the large marcasite aggregates without pyrrhotite have a texture identical to that described by Edwards (1954, Fig. 129) as lamellar marcasite pseudomorphs after pyrrhotite. In the T-2 lens, marcasite occurs as large spongy to lamellar masses associated with non-sulphide gangue in drillhole T-51.

Digenite and covellite occur in all of the Tulks lenses as hairline veinlets and rims, and as minute specks intermingled with other oxidation products (Figs. 10-13). The two copper sulphides are commonly intergrown, but either may predominate in an individual polished section or over a large part of a lens. For the Tulks deposit as a whole, a very rough estimate is that digenite exceeds the volume of covellite by a factor of four or five.

Of the various primary sulphides, galena has been by far the most susceptible to oxidation and supergene replacement by covellite and digenite. The commonest expression of galena alteration is the appearance of anglesite ($PbSO_4$) as spots and dappled areas near galena grain margins (Figs. 10-12). A frequent effect of anglesite alteration is that it imparts to galena the illusion of a rough or pebbled surface (Fig. 10).

Aside from its presence at the margins of galena, anglesite also occurs sparingly in several specimens as grey to white, cloudy pockets averaging about 0.5 mm in diameter. One sample (T-99-119) contains about 5% anglesite as clear, well-crystallized grains and aggregates; individual

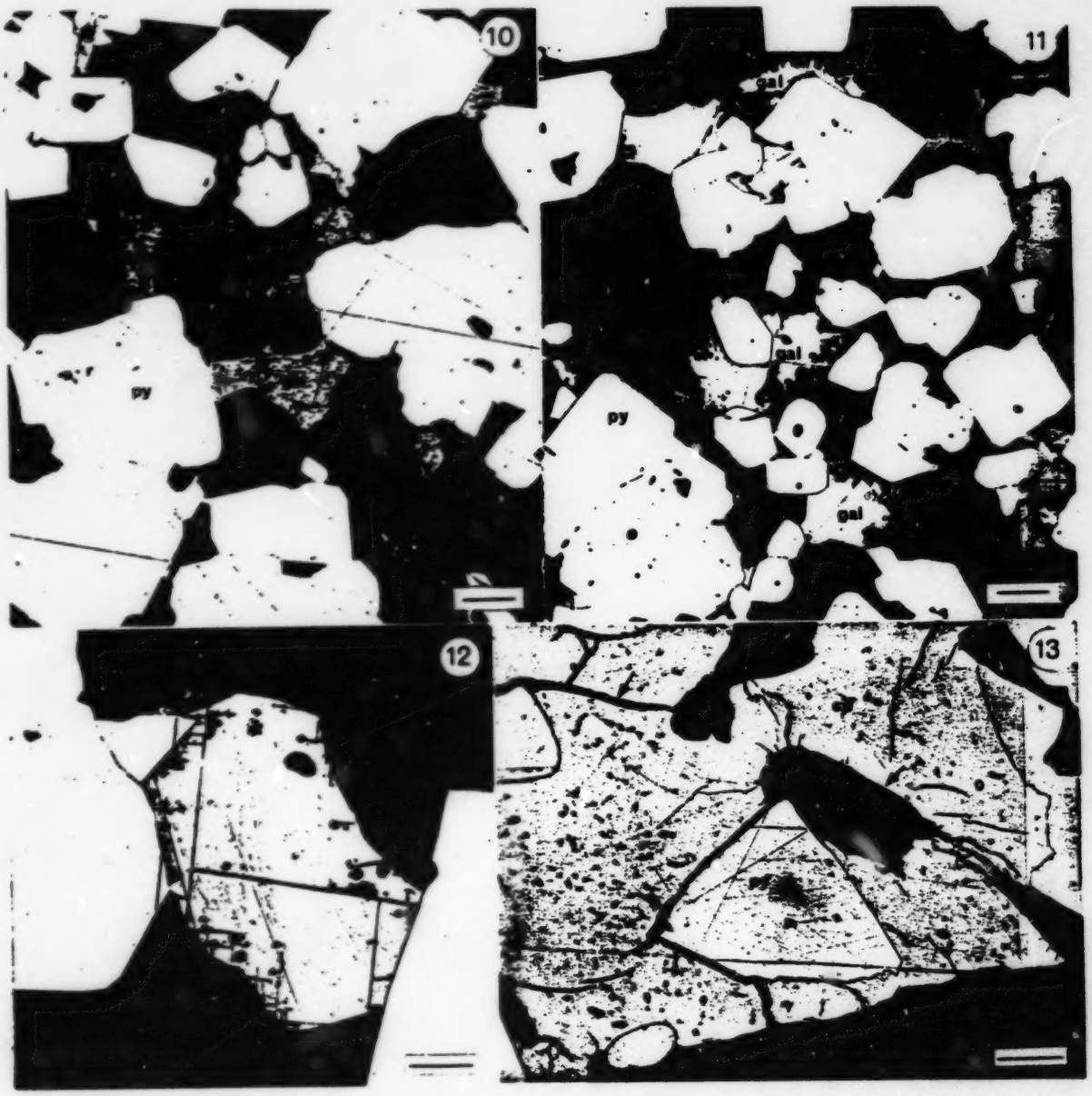

Fig. 10 - Pyrite and sphalerite with typically finer-grained galena; alteration of the galena to anglesite is evident from the darkened margins and spotty interiors of the galena grains. T-99-117, reflected light, air; scale represents 0.05 mm.

Fig. 11 - Extensive alteration of galena to mixtures of anglesite and digenite-covellite, and typical replacement of sphalerite by digenite-covellite hairline veinlets (e.g., at arrow). T-71-100, reflected light, air; scale represents 0.05 mm.

Fig. 12 - Cleavage-trace enhancement and spotty alteration of galena, predominantly by covellite. T-71-99, reflected light, oil immersion; scale represents 0.025 mm.

Fig. 13 - Intense replacement of chalcopyrite (cp) by digenite (e.g. at arrows) which occurs as hairline veinlets and as rims at the margins of pyrite and quartz (q). T-51-149, reflected light, oil immersion; scale represents 0.025 mm.

crystals of the anglesite are up to 0.2x0.2 mm.

Cerussite has been identified as one of the components of the fine-grained alteration mixtures at the borders of galena grains. This type of occurrence is similar to that of anglesite, though cerussite is apparently comparatively rare.

Kaolinite occurs in pockets which are similar in size and appearance to those of anglesite; kaolinite differs slightly in that its colour is solid white and the pockets of material are generally less cohesive than those of anglesite. Fourteen occurrences of kaolinite in the T-1, T-3, and T-4 lenses have been confirmed by X-ray powder patterns; some of these occurrences are shown on the diagrams illustrating digenite-covellite distribution (e.g. Figs. 18, 20).

Goethite is evident megascopically as a rusty alteration on the surfaces of a few drill cores. The mineral also was observed in a few polished sections, where minute irregular grains, rims, and reticulated veinlets occur in the non-sulphide gangue. Only rarely is goethite in contact with sulphides, and alteration of sulphides to goethite is negligible.

T-1 LENS

The T-1 lens is in the western part of the Tulks map area (Fig. 1). Cores from four drillholes in a single cross-section (Fig. 14) were examined to obtain a general assessment of the mineralogy of the lens. The polished-section sample interval for the sulphide-rich parts of each drillhole was less than one metre. Figure 15 shows the location of the samples with respect to the T-1 sulphide zones as interpreted both from the geological cross-section (Fig. 14) and the more detailed information available in the drillhole logs.

The principal base-metal sulphides - sphalerite, galena and chalcopyrite - occur throughout the cross-section. As assay data are unavailable for this study, metal variations are not evaluated here. The mineralogical trends, however, indicate that galena is concentrated in the northern (up-hole) side of the lens whereas chalcopyrite shows the opposite trend. These variations may not be evident in assay data because the absolute abundance of each mineral also seems to decline from north to south; nevertheless, the spatial prevalence of the pyrite-chalcopyrite-sphalerite assemblage versus that bearing galena is in accord with normal metal zoning, that is, the T-1 lens is not overturned and its stratigraphic top faces north.

The distribution of minor minerals in the T-1 lens is shown in Figure 15. In drillhole T-1 the abundance of tetrahedrite-tennantite is a low fraction of a percentage (designated as sparse in Figure 15), but a single polished section contains coarse megascopic masses amounting to about 15 vol. % of the sample. In drillhole T-2, one of the two areas designated as abundant (Fig. 15) contains about 2% tetrahedrite-tennantite, and the other contains a bit less than ½%. Similar variations in abundance from sample to sample are typical for the minor

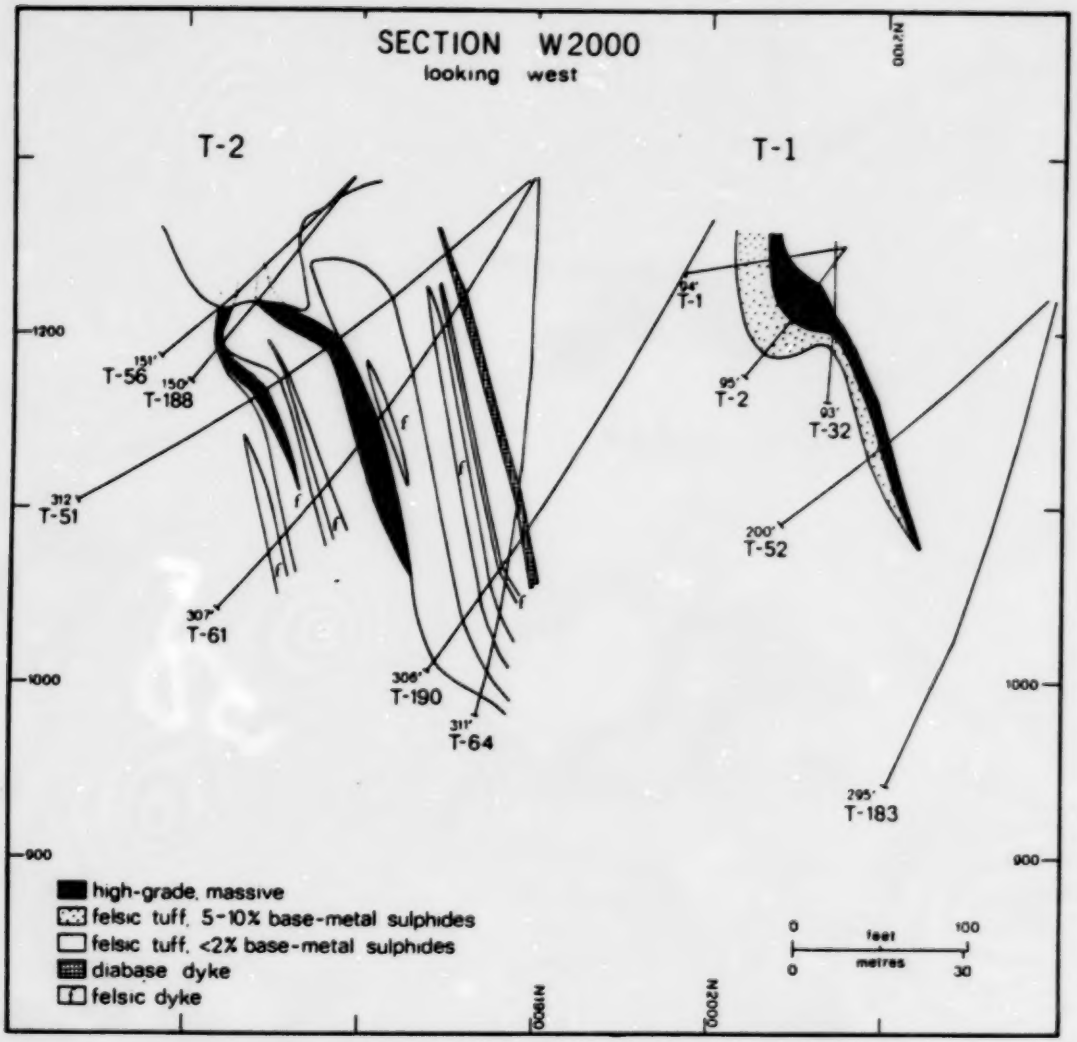

Fig. 14 - Cross-section of the Tulks T-1 and T-2 lenses.

minerals; the procedure adopted has been to specify their range in volume per cent for each drillhole, exactly as has been done for arsenopyrite and magnetite in Figure 15.

Microprobe analyses of tetrahedrite-tennantite from drillholes T-1 and T-2 are given in Table 3. The results show that substantial composition variations are present, even within an individual polished section; these variations are especially large for Sb and As, and formula compositions extend

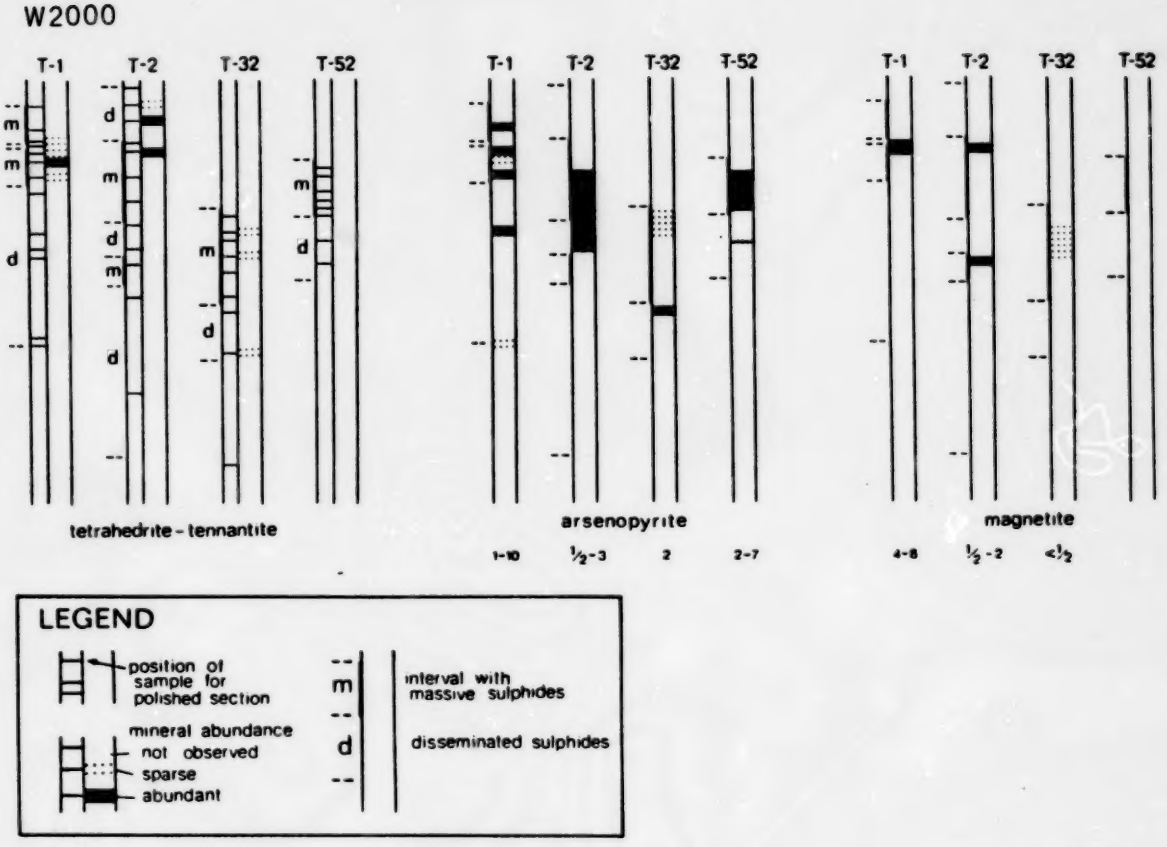

Fig. 15 - Distribution and relative abundance of tetrahedrite-tennantite, arsenopyrite, and magnetite in drill cores from the T-1 lens. Values given for arsenopyrite and magnetite are their ranges, in volume per cent, in the intervals designated as abundant (solid black). Location of the drillholes is in Figure 14; the vertical scale is as given in Figure 16.

well into the fields of both tetrahedrite and tennantite. Silver contents of the analyzed grains are fairly low, but the apparent absence of silver-bearing minerals other than aurian silver or argentian gold suggests that tetrahedrite-tennantite is the principal source of the silver in the T-1 lens.

The occurrence of arsenopyrite in the T-1 lens is noteworthy in that abundances (Fig. 15) are substantially higher than in any other Tulks lens.

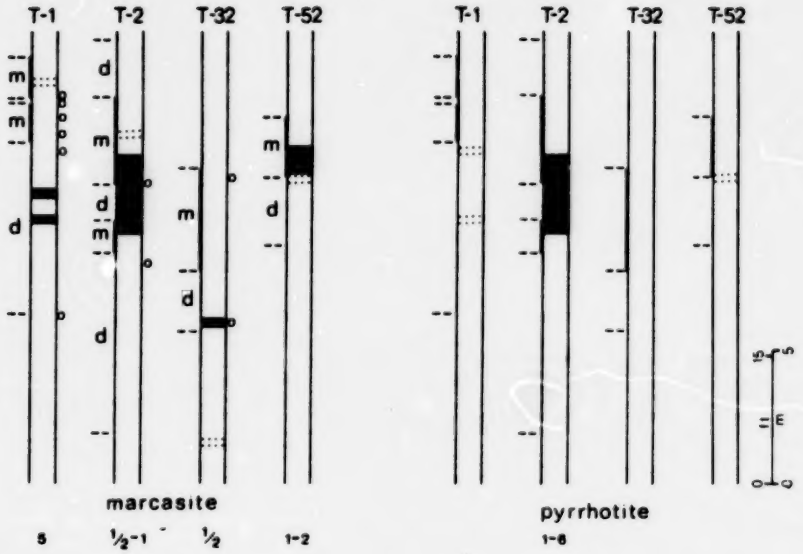

Fig. 16 - Distribution of marcasite and pyrrhotite in drill cores from the T-1 lens. Legend is as given in Figure 15; samples containing additional alteration minerals such as goethite, digenite-covellite, etc., are marked by an o.

Most of the arsenopyrite occurs as coarse crystals and polycrystalline grains, but a few high-grade samples contain fine-grained arsenopyrite concentrated in layers in sphalerite (Fig. 3).

The distribution of magnetite (Fig. 15) shows that the mineral decreases in abundance with increasing depth. Pyrrhotite, although generally sparse (Fig. 16), could be construed as having a trend similar to that of magnetite, but this variation is not evident if pyrrhotite is accepted as the precursor of marcasite.

Aside from the presence of marcasite, other mineral indicators of alteration are the occurrence of minute veins and patches of covellite-digenite and anglesite-cerussite on galena in samples from drillholes T-1 and T-32, the

occurrence of hairline-thin network veinlets of goethite in T-1, and the presence of traces of kaolinite in T-2. Most of the supergene copper sulphides are concentrated in near-surface drillhole T-1, and there is a notable decrease in these minerals at greater depths. Even in drillhole T-1 the overall intensity of sulphide alteration is weak and is almost wholly confined to grain-border replacement of galena.

T-2 LENS

The T-2 lens is near the T-1 lens, and thus both were sampled along the same cross-section line (Fig. 14). Only cores from drillholes T-56, T-51 and T-61 of the T-2 lens were examined microscopically.

Core recovery from the sulphide zone in drillhole T-56 was extremely low, and thus only five polished sections, all of massive sulphides, were studied. Sphalerite and chalcopyrite were found to be abundant, and galena to be sparse. Tetrahedrite-tennantite, arsenopyrite, magnetite etc. were not seen. One of the sections contains sparse marcasite, and three contain extensive digenite-covellite alteration.

Both the northern and southern massive sulphide segments intersected by drillhole T-51 were studied. Sparse tetrahedrite-tennantite occurs in all but the last metre of the northern segment but was unobserved in the southern. Sparse arsenopyrite was found in the southern segment only. Marcasite occurs only in the first metre of the southern segment, and its abundance ranges from 1% to 5%; one of the polished sections from this zone contains several blebs of gold.

The down-dip extension of the northern segment of the T-2 lens was intersected by drillhole T-61 from footages 165.5 to 185.5 (Fig. 14). Tetrahedrite-tennantite, arsenopyrite, marcasite and pyrrhotite were not observed in the

twelve polished sections from this interval. Magnetite, ranging from ½% to 2%, is restricted to a zone from footages 174 to 183, inclusive.

Relative to the T-1 lens, T-2 is strongly altered in that fully half of the T-2 samples contain digenite-covellite replacement veinlets. The veinlets are thin and occur sparingly in the deepest drillhole (T-61), and are wider and and more numerous in samples from the drillholes nearer surface. Whereas digenite-covellite replacement in the T-1 cross-section is associated mainly with galena, the principal affiliation in the T-2 section is with chalcopyrite and sphalerite.

T-3 LENS AND PART OF T-4

Five north-south cross-sections of the T-3 lens were studied. The most westerly of these sections, at W5000 (Fig. 1), is in an area where drilling has shown that the sulphide zone thins prior to eventual pinch-out farther west. Only one drillhole (T-172) in the W5000 section contains appreciable sulphides, and these were examined in twelve polished sections. The principal sulphides (Table 1) are accompanied by sparse tetrahedrite-tennantite localized along the northern edge of the lens, and by sparse arsenopyrite which occurs only in the southernmost, last metre of the lens. Supergene alteration was not detected in any of the samples.

SECTION W4940

The W4940 cross-section marks the western extremity of the underground workings from which the mill-tested bulk sample was extracted. The distribution of the massive sulphides and the location of the drillholes sampled are shown in Figure 17. The high-grade zone in drillhole T-62 contains all of the principal sulphides in abundance; the down-hole pyritite zone is more sulphide-rich

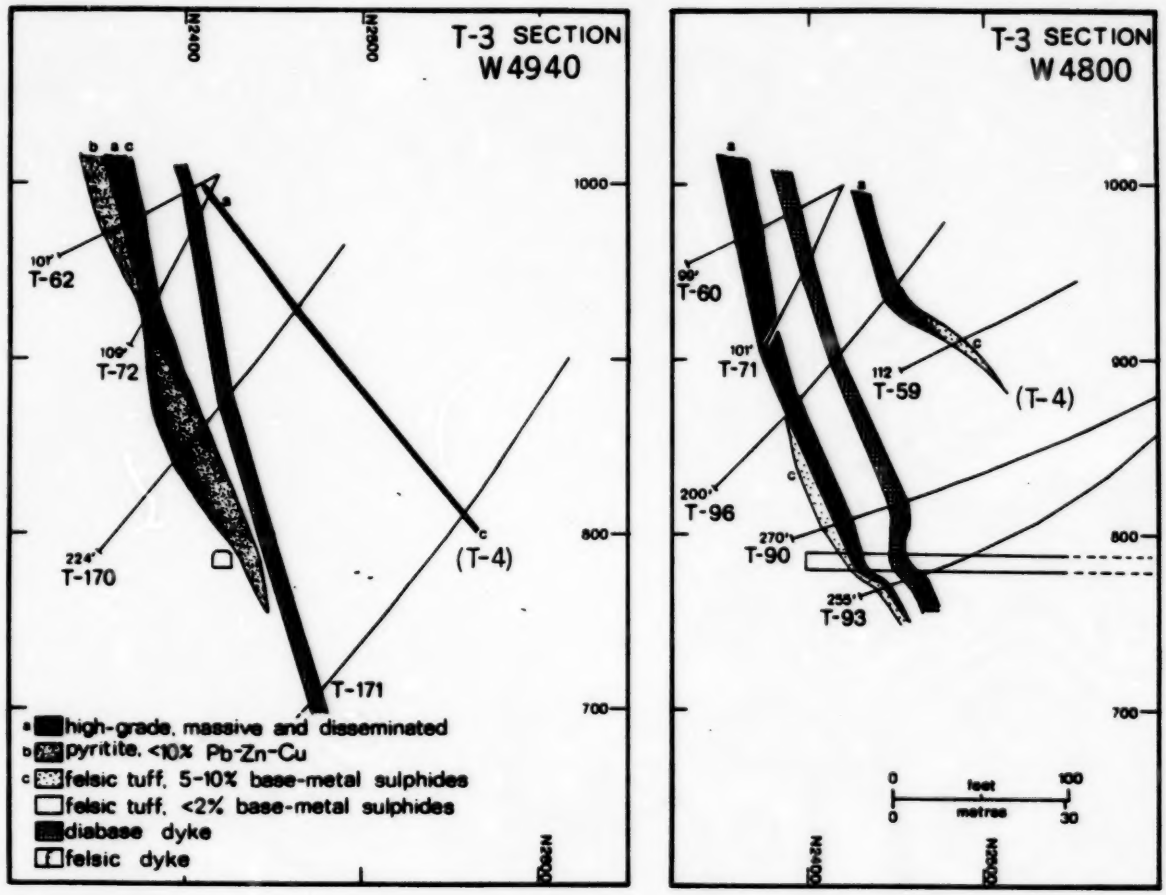

Fig. 17 - Cross-sections W4940 and W4800 of the T-3 and T-4 lenses.

and consists of compact, massive pyritite which has low base-metal grades. Within this low-grade zone the ratio of chalcopyrite to sphalerite+galena is high, and thus in relative terms the pyritite is a chalcopyrite-rich zone. At greater depth the sulphide lens, as exemplified by the intersection in drillhole T-170 (Fig. 17), is reversed in zoning: massive, compact pyritite with low metal grades and relative enrichment in chalcopyrite is succeeded down-hole by a less pyritiferous zone containing abundant sphalerite and galena.

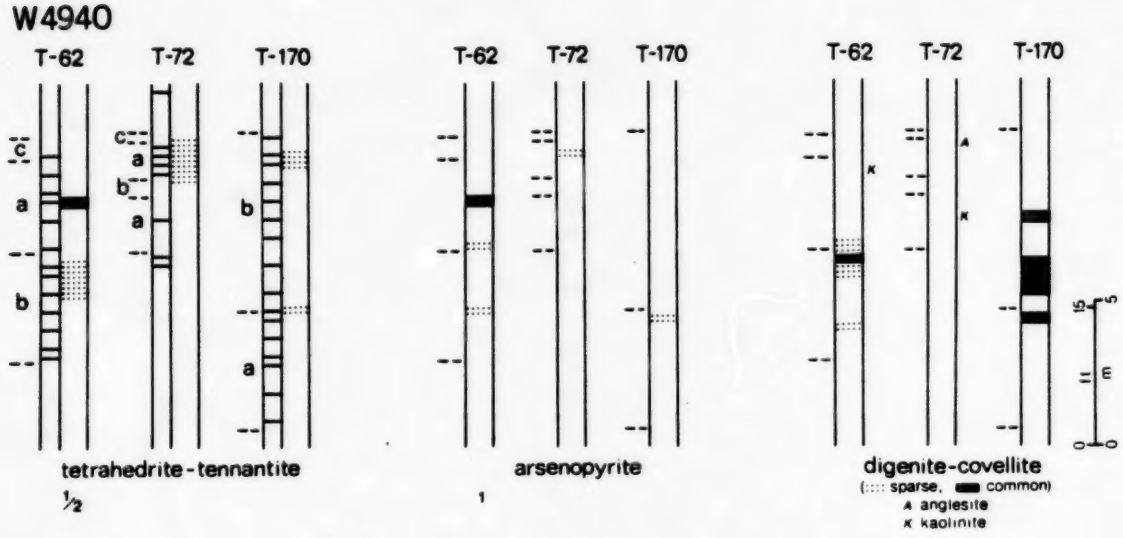

Fig. 18 - Distribution of tetrahedrite-tennantite, arsenopyrite, and secondary minerals in the W4940 cross-section of the T-3 lens. Legend is as shown in Figure 15, and sulphide zones are shown in Figure 17.

The distribution of some of the minor minerals in the W4940 cross-section is shown in Figure 18. Aside from the absence of magnetite, which therefore is not illustrated, a notable feature is the paucity of arsenopyrite in comparison with occurrences in the T-1 lens (Fig. 15). Tetrahedrite-tennantite is meager, and for the most part each occurrence is represented by only one or two small grains. Microprobe analyses of grains from the sole occurrence rated as abundant (T-62-55) shows that the grains are silver-rich (Table 3). Several blebs of gold were observed in samples from drillhole T-62 (Table 4). Traces of tellurides, including hessite (Ag_2Te), occur near the bottom of the sulphide zone intersected by drillhole T-170.

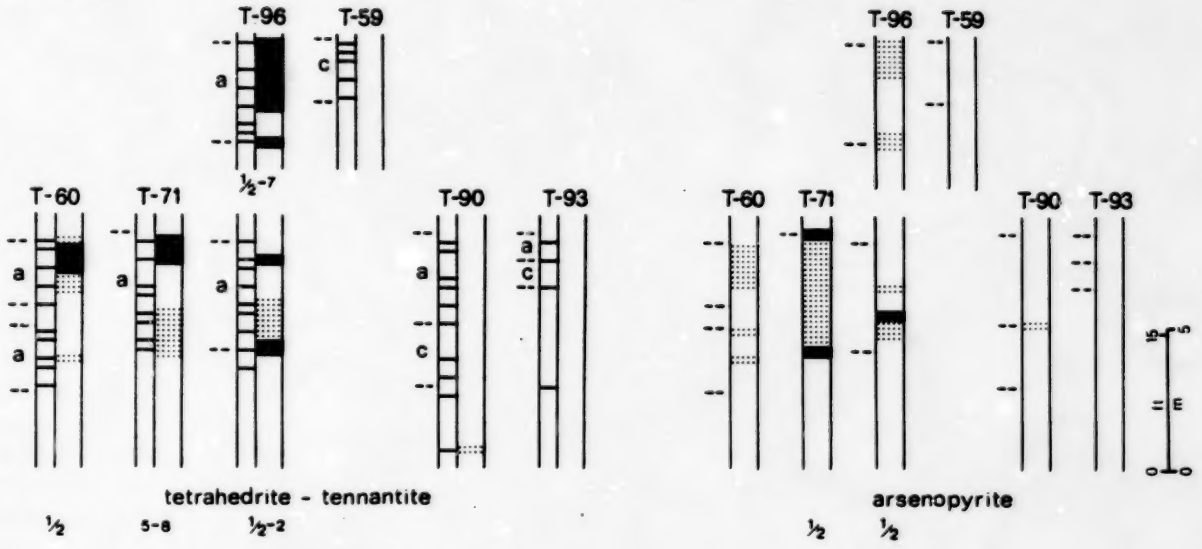

Fig. 19 - Distribution of tetrahedrite-tennantite and arsenopyrite in the W4800 cross-section of the T-3 and T-4 lenses. Legend is as shown in Figure 15, and sulphide zones are shown in Figure 17.

Supergene alteration the near-surface part of the cross-section is weak (Fig. 18). Digenite-covellite was not detected in samples from drillhole T-72, and the anglesite occurrence (Fig. 18) precedes the main massive sulphide zones. Most of the alteration in drillhole T-170 is represented by rims and veinlets of digenite rather than covellite, and some of the galena has the speckled appearance characteristic of alteration to anglesite.

SECTION W4800

The W4800 cross-section contains two major sulphide lenses (Fig. 17). The larger lens is T-3, and the more northerly, smaller lens is interpreted to be the eastern continuation of the T-4 lens (Fig. 1).

Distributions of the minor minerals in the cross-section are shown in Figure 19. In the T-3 lens, both tetrahedrite-tennantite and arsenopyrite have well-defined trends of decreasing abundance with increasing depth, and both

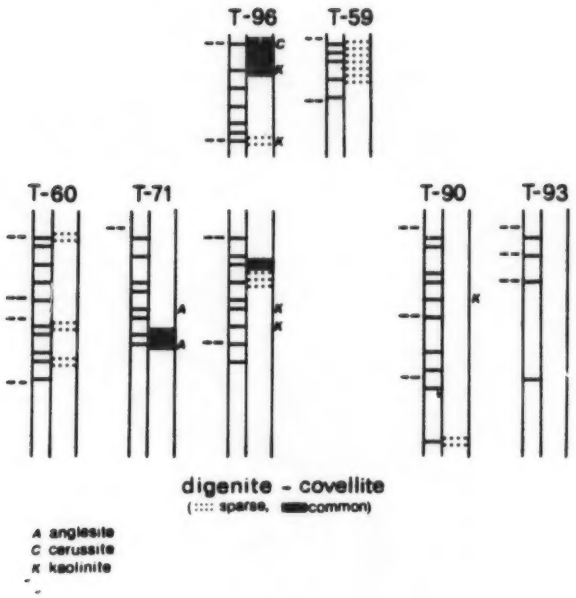

Fig. 20 - Distribution of digenite-covellite and other alteration minerals in the W4800 cross-section (Fig. 19).

are sparse in the vicinity of the underground workings (Fig. 17). In the T-4 lens, tetrahedrite-tennantite abundance in drillhole T-96 ranges from ½% to 3% except for the last sample (Fig. 19); the deeper, lower grade part of T-4 lens intersected in drillhole T-59 is devoid of both arsenopyrite and tetrahedrite-tennantite (Fig. 19). Magnetite and marcasite were not observed in either lens in the cross-section, and pyrrhotite occurs only as blèb inclusions in pyrite.

The distribution of digenite-covellite is shown in Figure 20. In the T-3 lens these sulphides are commonest at elevations above the level of the undergroung workings. Occurrences of digenite-covellite in drillhole T-60 are weak - the copper sulphides are localized rather than pervasive even in individual polished sections, and veinlets are widely spaced. The strong alteration

noted in one interval of drillhole T-71 (Fig. 20) consists predominantly of covellite; some of the covellite is relatively coarse-grained and in homogeneous aggregates up to 90x120 micrometers, by far the largest areas of this mineral seen in the Tulks samples. In the adjoining lower drillhole the predominant mineral is digenite.

Samples in which digenite and covellite are common usually also show irregular peripheral alteration of galena grains. This peripheral alteration is mainly anglesite, but the presence of cerussite also has been confirmed. Grey to white, turbid patches of anglesite up to 1 mm in diameter are occasionally visible on polished-section surfaces; these occurrences, as well as those of kaolinite, which have been confirmed by X-ray powder patterns are plotted on Figure 20.

SECTION W4705, T-4 LENS

The W4705 cross-section is shown in Figure 21. The initial intersections of massive sulphides are part of the T-4 mineralized horizon. The T-4 massive massive zone is characterized by a richness in tetrahedrite-tennantite (Fig. 22) and a paucity of chalcopyrite: about 90 per cent of the copper in the massive zone is attributable to tetrahedrite-tennantite. Samples from this interval in drillhole T-101 are low in galena, and those from T-99 are sparse in both galena and sphalerite.

The T-4 massive zone in drillhole T-101 occurs from footages 80 to 85.5; rocks both above and below this zone contain considerable amounts of disseminated sulphides. For example, half of the eight polished sections of samples from footages 26 to 58 contain 30 to 40 per cent pyrite. Much of the pyrite occurs as angular disseminated grains of diverse sizes and appears to be allogenic. The pyrite is accompanied by small amounts of chalcopyrite which consistently

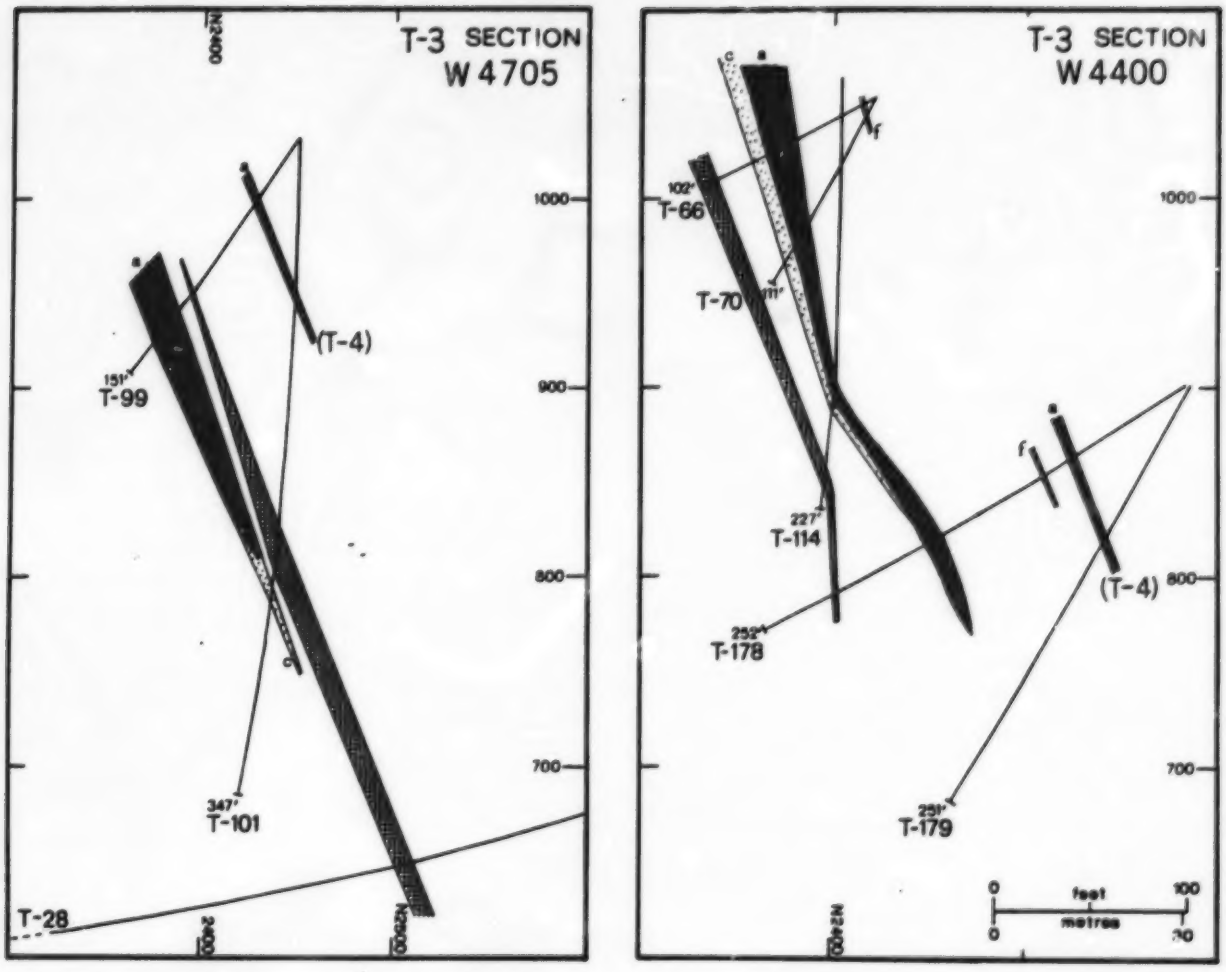

Fig 21 - Cross-sections of the T-4 and T-3 lenses at W4705 and W4400. Legend is as shown in Figure 17.

exceed the meager sphalerite and galena, and tetrahedrite-tennantite is notably absent. Rocks between the T-4 massive zone and the diabase dyke (Fig. 21) contain a different assemblage in that the total sulphide content is modest, but galena and sphalerite are common, and the small amount of chalcopyrite present nevertheless exceeds that of tetrahedrite-tennantite. Thus the anomalously high

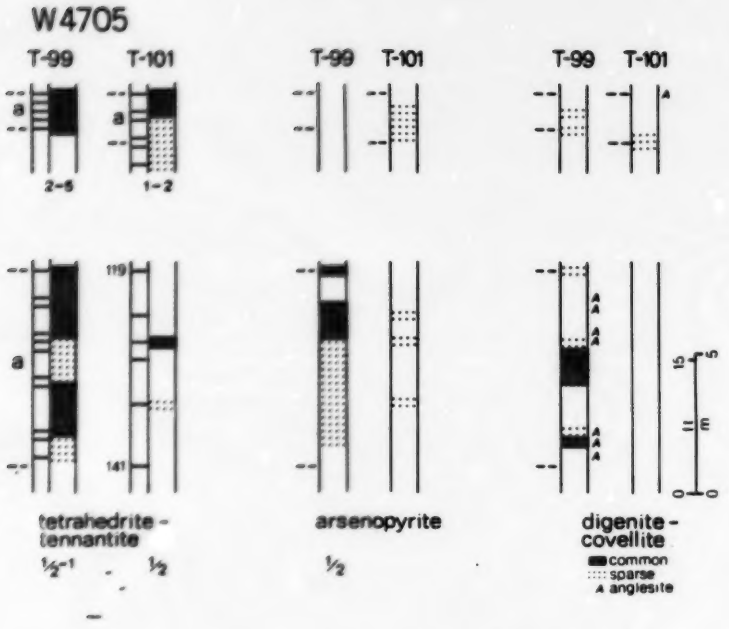

Fig. 22 - Distribution of minerals in the T-4 and T-3 lenses in the W4705 cross-section (Fig. 21).

ratio of tetrahedrite-tennantite to chalcopyrite consistently found for the T-4 massive zone is apparently strictly confined to this body.

The T-4 lens contains traces of digenite-covellite, but the chief alteration is apparently oxidation rather than supergene enrichment. All of the polished sections from drillhole T-99 and most from T-101 contain microscopic amounts of goethite.

SECTION W4705, T-3 LENS

Figure 22 shows the distribution of tetrahedrite-tennantite and arsenopyrite in the T-3 lens intersected by drillhole T-99. Data plotted for drillhole

T-101 are for an interval of disseminated sulphides (footages 119 to 141) above the diabase dyke; seven polished sections of samples from below the dyke contain a normal assemblage of principal sulphides and nothing unusual.

Supergene alteration in the W4705 cross-section is largely confined to that part of the T-3 lens intersected by drillhole T-99 (Fig. 22). The main secondary sulphide is covellite rather than digenite. Additionally, more than half of the polished sections contain galena grains showing small amounts of rim alteration to anglesite. Indeed, for the cross-section as a whole, the main mineral attacked by the alteration processes has been galena; the other sulphides, with only minor local exceptions, have not been affected.

SECTION W4400

The W4400 cross-section is shown in Figure 21. The T-4 horizon intersected in drillhole T-178 consists of pyritite with only very small amounts of chalcopyrite and only traces of galena and sphalerite. Other than a few pyrrhotite blebs in pyrite, no other sulphides were observed in four polished sections of pyritite. The downward extension of the T-4 lens, intersected by drillhole T-179, was not examined.

The T-3 lens consists of massive, tightly packed pyritite near surface; with increased depth the total pyrite content apparently lessens, but the proportion of allogenic grains increases as indicated by the samples from drillhole T-114 (Fig. 21). At drillhole T-178, however, the main sulphide zone consists of irregular, possibly highly distorted veinlet sulphides.

Figure 23 shows the distribution of tetrahedrite-tennantite and arsenopyrite in the W4400 T-3 lens. The meagerness of these minerals in the near-surface drillholes seems to be indicative of a progressive diminution laterally, both

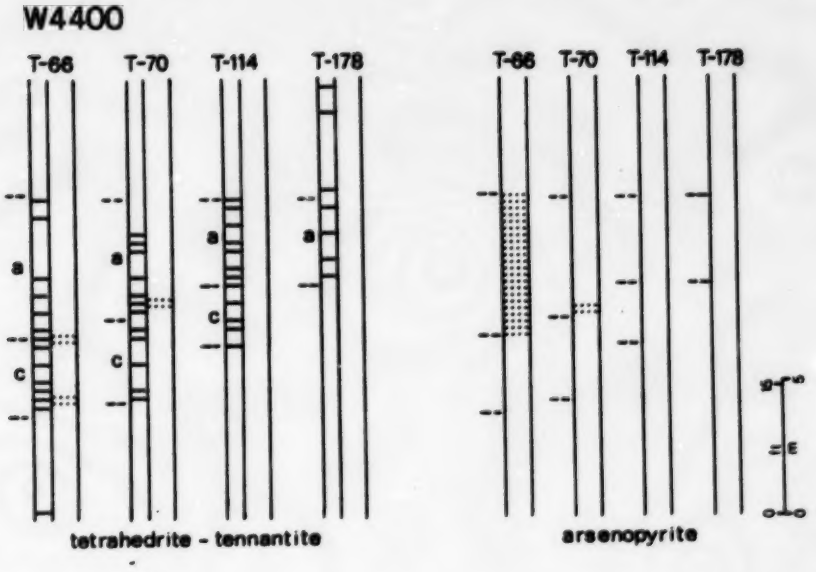

Fig. 23 - Distribution of tetrahedrite-tennantite and arsenopyrite in the T-3 lens at W4400 (Fig. 21).

to the east and west, from a focal point in the vicinity of W4800.

The three uppermost drillholes in the W4400 section have a normal sulphide assemblage consisting only of the principal sulphides, a few pyrrhotite bleb inclusions in pyrite, and traces of gold (Table 4). In contrast, the sulphide assemblage in T-178 consist of coarse pyrite and chalcopyrite in which the pyrite crystals commonly exceed 1 mm along an edge. The polished sections have a pyrite: chalcopyrite ratio of roughly 1:1, sphalerite is but a low fraction of a per cent of total sulphides, galena content is negligible, and sparingly disseminated tellurides are present. The main silicate minerals are quartz and chlorite.

Digenite-covellite alteration in the cross-section is extremely weak and has been observed only in samples from drillhole T-66. Some of the galena from T-66 also has barely perceptible alteration rims of anglesite.

MILL SAMPLES

The mill samples refer to those stored in two steel drums at Buchans and which represent portions of the Tulks bulk sample tested in the mill at Buchans. One drum contains coarse, sized material ranging from approximately 1.5x2x3 cm to 1x1.2x2 cm, and the other drum contains finely crushed material, variable from powdery to a maximum of 0.75x0.75x1 cm. Samples in both drums span the spectrum from high-grade, zinc-rich ore to phyllite containing only minor disseminated pyrite.

The underground site from which the bulk sample was extracted is shown in Figure 24. As noted in the Introduction, all or most of the bulk sample apparently was taken from the lower grade pyritite zone.

Eighteen polished sections were prepared from an equal number of hand samples from the drum of coarser material. Seven of the sections have sulphide contents of 15 to 50%, and in the remainder the sulphides exceed 50%. The sulphide assemblage consists almost wholly of the principal sulphides (Table 1); traces of pyrrhotite occur as bleb inclusions in pyrite, and two sections have blebs of tetrahedrite-tennantite, the largest approximately 25x30 micrometers in diameter, as inclusions in pyrite. No signs of oxidation or supergene alteration were seen.

Sixteen polished sections of samples from the drum of finer-sized material were prepared. Eleven of the sections consist of massive sulphides, and in all but one of the remainder the sulphide content is less than 20%. The sulphide assemblage is the same as noted for the coarse samples except that sparse tetrahedrite-tennantite was observed in three samples, and two contain supergene covellite and digenite. The tetrahedrite-tennantite grains are up to 30x60

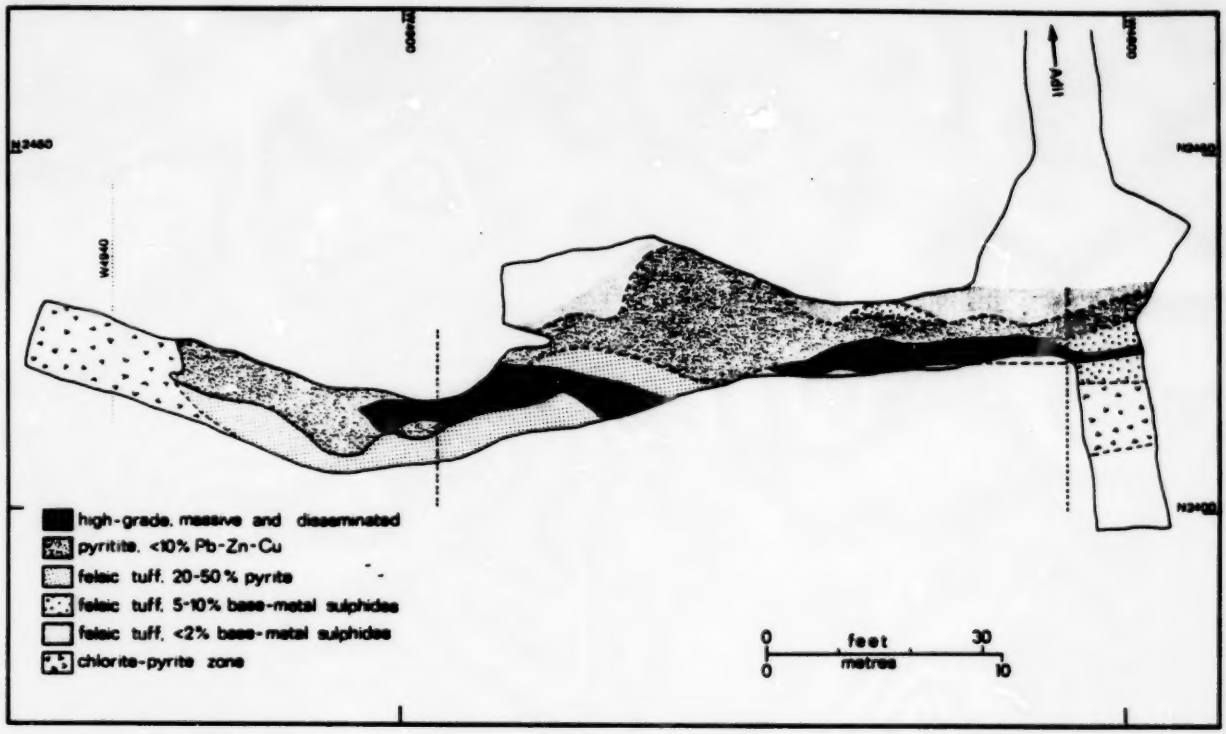

Fig. 24 - Plan showing the distribution of sulphide zones in the underground intersection of the T-3 lens. The bulk sample for milling tests was taken from the area between the dashed vetical lines near W4800 and W4900.

micrometers, but most are 30x30 micrometers and occur as inclusions in pyrite. The supergene sulphides are concentrated principally at the margins of galena, but a few border sphalerite, and traces occur as rims and veinlets in chalcopyrite.

Thin-section examination of the various mill-test samples shows that the principal silicate in pyritite is quartz, usually accompanied by abundant chlorite and muscovite. In sulphide-poor samples, either quartz or muscovite can predominate, and chlorite is subordinate to both. Minor amounts of calcite and dolomite generally accompany the silicates regardless of sulphide abundance.

The polished-section study of the mill-test samples indicates that the

massive, compact pyritite (>90% sulphides) is generally low in total ore-mineral content despite a relative enrichment in chalcopyrite. The bulk of the galena and sphalerite seems to be concentrated in a few high-grade specimens rather than in numerous medium-grade ones.

In general aspect, the mill-test samples are not significantly different from the drill-core samples of the T-3 lens. Microscopic study of the mill-test samples preceded that of the cores because it was thought that this sequence would provide an initial focus on the mineralogical problem, and the subsequent drillcore study would provide a better sense of the spatial distribution of the textures or minerals which have impaired the metal recoveries. In this connection, a feature noted in a couple of the high-grade mill samples is that some of the sulphide layers are fine-grained and somewhat complex because of partial replacement of sphalerite by galena and chalcopyrite. The subsequent study of the drill cores showed that this type of intergrowth texture is rare in the T-3 lens and would be inconsequential with respect to ore processing.

The relatively weak and apparently uneven distribution of supergene alteration in the mill-test samples is considered to be appropriate in the light of the drill-core study. The bulk sample was extracted from a deep part of the T-3 lens (Fig. 17), in an area where adjacent cross-sections show considerable variation in digenite and covellite contents (Figs. 18, 20).

SUMMARY OF ECONOMIC MINERALOGY

1. Grain sizes and textures of the sulphides are similar in all of the Tulks lenses.
2. Grain sizes are not unusually fine, nor are the sulphide textures complex; neither of these properties should hinder the achievement of an adequate liberation of ore minerals.
3. The primary mineral sources of lead and zinc are almost exclusively galena and sphalerite. Chalcopyrite accounts for nearly all of the copper in the T-1 and T-2 lenses, and in all except minor, localized parts of the T-3 lens wherein tetrahedrite-tennantite is abundant. In the eastern extremity of the T-4 lens, however, tetrahedrite-tennantite accounts for most of the copper.
4. Argentian tetrahedrite-tennantite and native gold have sufficiently widespread distributions and abundances to account for nearly all of the silver and gold values in the deposit.
5. Variations in the proportions of sulphide minerals occur both along and across the stratigraphy of the massive sulphide zones. Variations along the stratigraphy occur both horizontally and with depth. In the T-3 lens, tetrahedrite-tennantite and arsenopyrite consistently decrease with depth.
6. Magnetite, pyrrhotite and marcasite have been found in significant amounts only in the T-1 and T-2 lenses.
7. The principal major non-sulphide gangue mineral is quartz, and the principal minor ones are muscovite, chlorite, and dolomite. Less pervasive are calcite, barite, albite, and celsian.

8. All of the Tulks lenses have been affected by oxidation and supergene enrichment. The chief manifestation of these alterations is the presence of anglesite, digenite, and covellite.

9. Galena has been the most susceptible to attack by the secondary alteration processes. Sphalerite and chalcopyrite have been affected much less in terms of (a) the spatial extent of alteration, (b) the intensity of alteration of individual grains, (c) the complexity of alteration products, and (d) the potential liberation of alteration-free grains:

   (a) weak alteration of galena is evident in several areas where there is no visible alteration of sphalerite or chalcopyrite;

   (b) many galena grains show substantial replacement around rims and cleavage traces; in contrast, the volume of associated sphalerite and chalcopyrite affected by alteration is smaller despite the quantitative predominance of sphalerite in the ore;

   (c) galena alteration commonly consists of complex mixtures involving anglesite, digenite, and covellite; most of the sphalerite and chalcopyrite alteration consists of replacement by digenite;

   (d) rim alteration of galena is invariably accompanied by substantial penetration of the secondary minerals into the interior of the galena grains, thus considerably diminishing the size of the particles that will be completely free of alteration in the crushed ore; in contrast, the same grind will yield mainly fresh sphalerite because (i) sphalerite is coarser than galena and fewer rims have been altered; (ii) alteration of sphalerite is represented mainly by widely spaced, short hairline veinlets. In other words, whereas alteration of galena is commonly pervasive, large areas of so-called altered sphalerite are pristine.

CONCLUSIONS AND RECOMMENDATIONS

The mineralogical study of the Tulks ore was undertaken to provide fundamental documentation of the character and distribution of the primary and secondary mineral assemblages, and to establish, if possible, the factors that might have led to poor recoveries in the milling tests. The results of the microscopic study indicate that the primary ore at Tulks is relatively simple in mineralogy and is of sufficient coarseness to yield adequate metal recoveries. Minor metal losses from primary ore will arise mainly because of bleb inclusions locked in pyrite, and because of incomplete liberation of some of the finer-grained sulphides which occur among the interstices of pyrite grains. Neither of these losses is thought to be a metallurgical problem of major consequence because the bulk of the interstitial sulphides is considered to be amenable to liberation. Various ASARCO bench tests of Tulks ore yielded poor metal recoveries, but in most of the tests the grind was 80% minus 200 mesh. This grind is considered here to be too coarse for run-of-the-mill Tulks ore; it is concluded that, aside from flotation chemistry, an inadequately fine grind was the single most important factor contributing to poor recoveries in the bulk-sample tests.

All of the Tulks lenses have been altered, both by oxidation and by deposition of supergene sulphides. Although the effects of these alterations generally decrease with depth, the trend is by no means rigid. Thus it is difficult to assess whether the mill-tested bulk sample was representative of average altered ore, but on the basis of the polished-section studies it is thought that the bulk sample was only slightly below average in its amount of

digenite-covellite alteration, and was totally unrepresentative of the oxidation which occurs at higher elevations in the T-3 lens. Because of alteration of galena to anglesite and other minerals, it is anticipated that lead recoveries will be lower than those obtained from the apparently unoxidized bulk sample. On the other hand, overall covellite-digenite alteration probably constitutes less than 0.01% of the ore, and thus it is possible that the detrimental effects of these copper sulphides on the flotation of the primary sulphides can be overcome by cyanide addition. It is recommended that a sample more representative of the Tulks ore be obtained, either by using a large weight of drill core or by raising into the T-3 lens, that new flotation tests be undertaken, that the tests be bench-scale rather than involving the Buchans mill, and that a finer grind be used for the feed.

ACKNOWLEDGMENTS

Access to the Tulks drill cores, and pertinent information such as cross-sections of the Tulks deposit, were obtained through the cooperation of Abitibi-Price and the particular assistance of D. Barbour and J.G. Thurlow of the company's Mineral Resources Division. Laboratory studies at CANMET were aided by the help of J.Y. Bourgoin and J.M. Beaulne, who prepared the polished sections and thin sections, respectively; E.J. Murray and P. Carrière assisted with the X-ray studies, and D.R. Owens provided all of the invaluable electron microprobe data incorporated in this report.

REFERENCES

Barbour, D. "Geology and mineralization of the Tulks area"; Company Report, Abitibi-Price Mineral Resources Division; Feb. 1978.

Edwards, A.B. "Textures of the ore minerals and their significance"; Australian Inst Mining Metall; 1954.

Fleet, M.E. "The pyrrhotite-marcasite transformation"; Can Mineral 16:31-35; 1978.

Kean, B.F. "Geology of the Victoria Lake map area, Newfoundland (12A/6); Mineral Development Division Report 77-4; Newfoundland Department of Mines and Energy; 1977.

Kissin, S.A. and Owens, D.R. "New data on stannite and related tin sulfide minerals"; Can Mineral 17:125-135; 1979.

Schemerhorn, L.J.G. "The deposition of volcanics and pyritite in the Iberian Pyrite Belt"; Mineralium Deposita 5:273-270; 1970.